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Measurement of B_s^0 meson production in pp and PbPb collisions at $\sqrt{s}NN = 5.02$ TeV

CMS Collaboration ; Canelli, Maria Florencia ; Kilminster, Benjamin ; Aarrestad, Thea K ; Brzhechko, Danyyl ; Caminada, Lea ; de Cosa, Annapaoloa ; Del Burgo, Riccardo ; Donato, Silvio ; Galloni, Camilla ; Hreus, Tomas ; Leontsinis, Stefanos ; Mikuni, Vinicius Massami ; Neutelings, Izaak ; Rauco, Giorgia ; Robmann, Peter ; Salerno, Daniel ; Schweiger, Korbinian ; Seitz, Claudia ; Takahashi, Yuta ; Wertz, Sebastien ; Zucchetta, Alberto ; et al

DOI: https://doi.org/10.1016/j.physletb.2019.07.014

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ZORA URL: https://doi.org/10.5167/uzh-180093
Journal Article
Published Version

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Originally published at:
CMS Collaboration; Canelli, Maria Florencia; Kilminster, Benjamin; Aarrestad, Thea K; Brzhechko, Danyyl; Caminada, Lea; de Cosa, Annapaoloa; Del Burgo, Riccardo; Donato, Silvio; Galloni, Camilla; Hreus, Tomas; Leontsinis, Stefanos; Mikuni, Vinicius Massami; Neutelings, Izaak; Rauco, Giorgia; Robmann, Peter; Salerno, Daniel; Schweiger, Korbinian; Seitz, Claudia; Takahashi, Yuta; Wertz, Sebastien; Zucchetta, Alberto; et al (2019). Measurement of B_s^0 meson production in pp and PbPb collisions at $\sqrt{s}NN = 5.02$ TeV. Physics Letters B, B796:168-190.
DOI: https://doi.org/10.1016/j.physletb.2019.07.014

Physics Letters B 796 (2019) 168–190

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of B_s^0 meson production in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration *

CERN, Switzerland

ARTICLE INFO

Article history:
Received 6 October 2018
Received in revised form 27 June 2019
Accepted 4 July 2019
Available online 9 July 2019
Editor: M. Doser

Keywords:
Physics
Quark gluon plasma
B meson
Open heavy-flavor

ABSTRACT

The production cross sections of B_s^0 mesons and charge conjugates are measured in proton-proton (pp) and PbPb collisions via the exclusive decay channel $B_s^0 \to J/\psi\phi \to \mu^+\mu^-K^+K^-$ at a center-of-mass energy of 5.02 TeV per nucleon pair and within the rapidity range $|y| < 2.4$ using the CMS detector at the LHC. The pp measurement is performed as a function of transverse momentum (p_T) of the B_s^0 mesons in the range of 7 to 50 GeV/c and is compared to the predictions of perturbative QCD calculations. The B_s^0 production yield in PbPb collisions is measured in two p_T intervals, 7 to 15 and 15 to 50 GeV/c, and compared to the yield in pp collisions in the same kinematic region. The nuclear modification factor (R_{AA}) is found to be $1.5 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$ for 7–15 GeV/c, and $0.87 \pm 0.30(\text{stat}) \pm 0.17(\text{syst})$ for 15–50 GeV/c, respectively. Within current uncertainties, the B_s^0 results are consistent with models of strangeness enhancement, and suppression by parton energy loss, as observed for the B^+ mesons.

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1. Introduction

Relativistic heavy ion collisions allow the study of quantum chromodynamics (QCD) at high energy density and temperature. Under such extreme conditions, a state consisting of deconfined quarks and gluons, the quark-gluon plasma (QGP) [1,2], is predicted by lattice QCD calculations [3]. The study of the phenomenon in which the outgoing partons interact strongly with the QGP and lose energy by means of elastic collisions and medium-induced gluon radiation [4–8] can provide insights into the energy density and diffusion properties of the QGP. Heavy quarks are effective probes to study these properties of the medium. Charm and beauty quarks that are primarily produced in hard scatterings at the early stages of the collision are expected to carry the full evolution history of the QGP formation [8]. On the other hand it is expected [9] that, via the process $gg \to s\bar{s}$, an enhancement of strangeness in a thermally and chemically equilibrated QGP should occur if its temperature is above the strange quark mass. Measurements at the BNL RHIC of the production of strange baryons and mesons, using different collision systems and beam energies, provide systematic support for this expectation [10–14]. Because of the interplay between the predicted enhancement of strange quark production and the quenching mechanism of beauty quarks, the measurement of strange beauty particles is important for studying the mechanisms of beauty hadronization in heavy ion collisions. In the presence of a medium with increased strangeness content [15,16], the relative yield of B_s^0 mesons with respect to nonstrange beauty mesons at transverse momentum (p_T) below $\sim$15 GeV/c [8,17] can be enhanced in nucleus-nucleus collisions compared to proton-proton (pp) interactions. This can happen if recombination is a significant factor of beauty hadronization in the QGP [18–20]. The recombination processes, which are considered markers for the presence of a deconfined medium, were most recently tested in the open charm sector by the ALICE Collaboration [21]. A possible hint for an enhancement in the relative yield of D_s^+ mesons with respect to nonstrange charmed mesons for $p_T < 8$ GeV/c in central PbPb collisions at a center-of-mass energy of $\sqrt{s_{NN}} = 5.02$ TeV per nucleon pair was observed.

The production of B_s^0 mesons was previously measured at the CERN LHC by the CMS Collaboration in pp collisions at a center-of-mass energy of $\sqrt{s} = 7$ TeV [22] and in proton-lead (pPb) collisions at $\sqrt{s_{NN}} = 5.02$ TeV [23]. In this letter, we report the first measurement of exclusive B_s^0 meson decays ever performed in nucleus-nucleus collisions and in pp collisions at 5.02 TeV. The pp measurement is performed as a function of p_T and compared to the predictions of fixed-order plus next-to-leading order logarithmic (FONLL) perturbative QCD calculations [24–26]. The nuclear modification factor (R_{AA}) of B_s^0 mesons, which is defined as the ratio of the yield in PbPb collisions with respect to that in pp collisions scaled by the corresponding number of binary nucleon-nucleon (NN) collisions, is shown. The comparison between the R_{AA} of B_s^0 mesons and that of B^+ mesons measured by CMS at the same energy [27] is also presented.

* *E-mail address:* cms-publication-committee-chair@cern.ch.

https://doi.org/10.1016/j.physletb.2019.07.014
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The B_s^0 meson and its charge conjugate are measured in the rapidity range $|y| < 2.4$ via the reconstruction of the decay channel $B_s^0 \to J/\psi\phi \to \mu^+\mu^-K^+K^-$, which has the branching fraction $\mathcal{B} = (3.12 \pm 0.24) \times 10^{-5}$ [28]. The pp measurement is performed as a function of the B_s^0 p_T in three intervals, 7–15, 15–20, and 20–50 GeV/c. The PbPb production yield and the R_{AA} measurement are performed in two p_T intervals, 7–15 and 15–50 GeV/c, inclusively for all events (i.e., 0–100% centrality, the degree of overlap of the two colliding nuclei). Throughout the letter, unless otherwise specified, the y and p_T variables given are those of the B_s^0 mesons. This analysis does not distinguish between the charge conjugates.

2. Experimental apparatus and data sample

The central feature of the CMS detector is a superconducting solenoid, which provides a magnetic field of 3.8 T. Within the solenoid volume are a silicon tracker that measures charged particles in the pseudorapidity range $|\eta| < 2.5$, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. For charged particles of $1 < p_T < 10$ GeV/c and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_T and 25–90 (45–150) μm in the transverse (longitudinal) impact parameter [29]. Muons are measured in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. The muon reconstruction algorithm starts by finding tracks in the muon detectors, which are then fitted together with tracks reconstructed in the silicon tracker to form "global muons". Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution for muons with $20 < p_T < 100$ GeV/c of 1.3–2.0% in the barrel ($|\eta| < 1.2$) and better than 6% in the endcaps ($1.6 < |\eta| < 2.4$). For muons with higher p_T up to 1 TeV/c, the p_T resolution in the barrel is better than 10% [30]. The hadron forward (HF) calorimeter uses steel as an absorber and quartz fibers as the sensitive material. The two halves of the HF are located 11.2 m away from the interaction point, one on each end, providing together coverage in the range $3.0 < |\eta| < 5.2$. In this analysis, the HF information is used for performing an offline event selection. A detailed description of the CMS experiment and coordinate system can be found in Ref. [31].

Several Monte Carlo (MC) simulated event samples are used to evaluate background components, signal efficiencies, and detector acceptance corrections. The simulations include samples containing only the B_s^0 meson decay channels being measured, and samples with inclusive (prompt and nonprompt) J/ψ mesons. Proton-proton collisions are generated with PYTHIA8 v212 [32] tune CUETP8M1 [33] and propagated through the CMS detector using the GEANT4 package [34]. The decay of the B_s^0 mesons is modeled with EVTGEN 1.3.0 [35], and final-state photon radiation in the B_s^0 decays is simulated with PHOTOS 2.0 [36]. For the PbPb MC samples, each PYTHIA8 event is embedded into a PbPb collision event generated with HYDJET 1.8 [37], which is tuned to reproduce global event properties, such as the charged-hadron p_T spectrum and particle multiplicity. For both samples, the signal p_T shape is reweighted to match the one from FONLL. For both pp and PbPb data and MC samples, the dimuon and ditrack mass distributions/resolutions are consistent.

Events were collected with the same trigger during the pp and PbPb data acquisition, requiring the presence of two muon candidates (with no explicit momentum threshold) in coincidence with a bunch crossing. For the offline analysis, events have to pass a set of selection criteria designed to reject events from background processes (beam-gas collisions and beam scraping events) as described in Ref. [38]. Events are required to have at least one reconstructed primary interaction vertex, formed by two or more tracks, with a distance from the center of the nominal interaction region of less than 15 cm along the beam axis. In PbPb collisions, the shapes of the clusters in the pixel detector have to be compatible with those expected from particles produced by a PbPb collision [39]. In order to select hadronic collisions, the PbPb events are also required to have at least three towers in each of the HF detectors with energy deposits of more than 3 GeV per tower. The combined efficiency for this event selection, including the remaining non-hadronic contamination, is (99 ± 2)%. Values higher than 100% are possible, reflecting the potential presence of ultra-peripheral (i.e., non-hadronic) collisions in the selected event sample. The PbPb sample corresponds to an integrated luminosity of approximately 351 μb^{-1}. This value is indicative only, as the PbPb yield is normalized by the total number of minimum bias events sampled, N_{MB} [38]. The pp data set corresponds to an integrated luminosity of 28.0 pb^{-1}, which is known to an accuracy of $\pm$2.3% from the uncertainty in the calibration based on a van der Meer scan [40]. The average number of additional collisions per bunch crossing is approximately 0.9 for pp and less than 0.01 for PbPb data. The presence of multiple collisions is found to have a negligible effect on the measurement.

3. Signal extraction

The analysis procedure is common for pp and PbPb data. Kinematic limits are imposed on the single muons so that their reconstruction efficiency stays above 10%. These limits are $p_T^{\mu} >$ 3.5 GeV/c for $|\eta^{\mu}| < 1.2$, $p_T^{\mu} > 1.8$ GeV/c for $2.1 \leq |\eta^{\mu}| < 2.4$, and linearly interpolated in the $1.2 < |\eta^{\mu}| < 2.1$ region. The muons are also required to match the muons that triggered the event online, and to pass selection criteria optimized for low p_T (the so-called *soft selection* [30]). Two muons of opposite sign (OS), with an invariant mass within $\pm$150 MeV/c^2 of the world-average J/ψ meson mass [28] are selected to reconstruct a J/ψ candidate, with a mass resolution of typically 18–55 MeV/c^2, depending on the dimuon rapidity and p_T. The OS muon pairs are fitted with a common vertex constraint and are kept if the p-value of the χ^2 of the fit is greater than 1%, thus lowering the background from charm and beauty hadron semileptonic decays. Similarly, the ϕ meson candidates are formed with a common vertex constraint between two OS charged-particle tracks with $p_T > 300(150)$ MeV/c for PbPb (pp) sample, both required to pass standard selections [38]. The invariant mass, with a resolution of $\sim$3.9 (3.4) MeV/c^2 for PbPb (pp) data, is required to be within 15 MeV/c^2 of the world-average ϕ meson mass [28]. The B_s^0 meson candidates are constructed by combining the J/ψ and ϕ candidates and requiring that they originate from a common vertex. Without using particle identification, assumptions need to be made about the masses of the charged particles. The difference between the natural width (according to PDG [41]) and the measured width (reflecting detector resolution) of the peaks is much bigger for the J/ψ meson than for the ϕ meson. Therefore, in calculating the mass of the B_s^0 candidates, the two charged particles are always assumed to have the mass of charged kaons, and the muon pair is assumed to have the mass of a J/ψ meson.

The B_s^0 candidates are selected according to their daughter charged particle track kinematics, the χ^2 probability of their decay vertex (the probability for the muon tracks from the J/ψ meson decay and the other charged particle tracks to originate from a common vertex), the distance between the primary and decay vertices (normalized by its uncertainty), and the pointing angle (the angle between the line segment connecting the primary and decay vertices and the momentum vector of the B_s^0 meson). The selection is optimized separately for pp and PbPb results as well as each individual p_T bin, using a multivariate technique that employs the boosted decision tree (BDT) algorithm [42], in order to

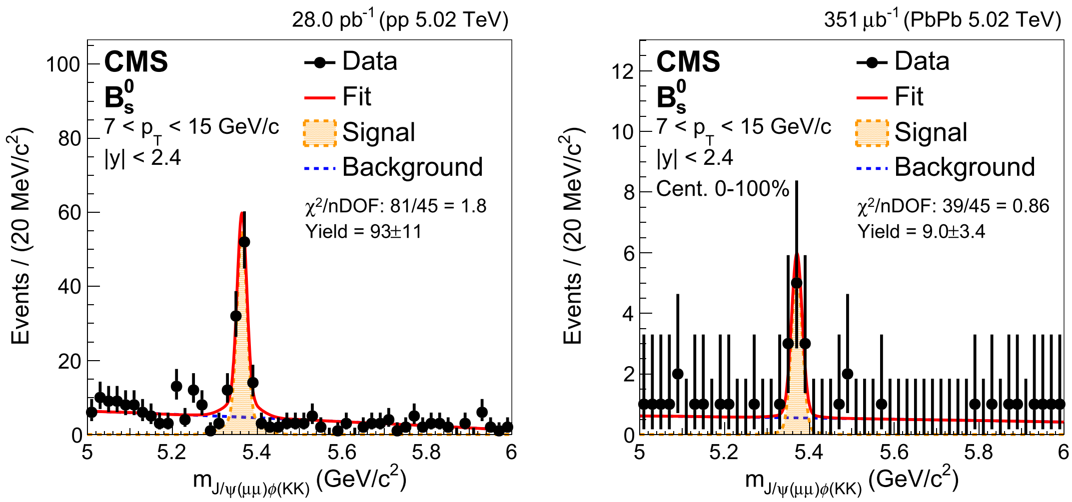

Fig. 1. Invariant mass distributions of B_s^0 candidates in pp (left) and PbPb (right) collisions measured in the range $|y| < 2.4$ and in the p_T range of 7–15 GeV/c. The χ^2 divided by the number of degrees of freedom (nDOF) is also given.

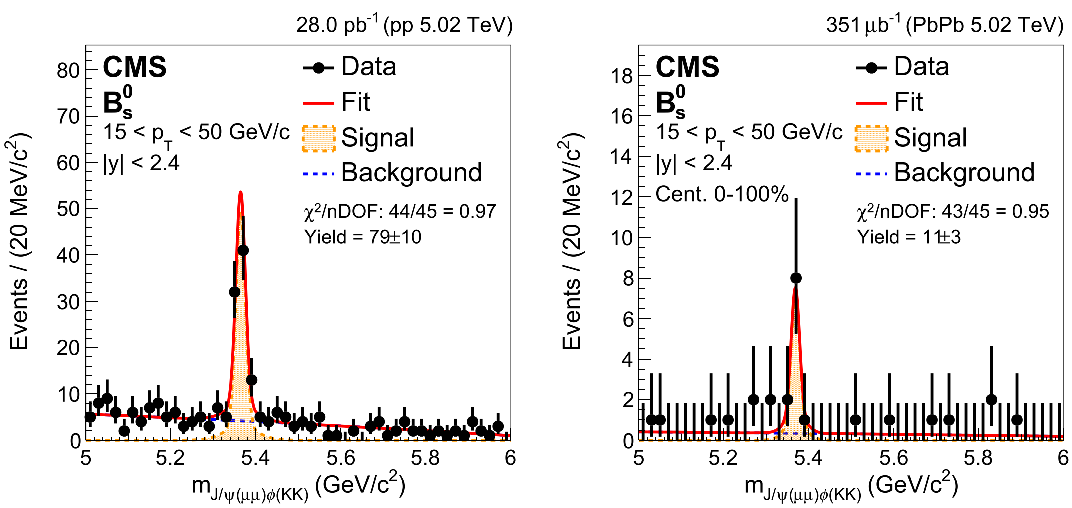

Fig. 2. Invariant mass distributions of B_s^0 candidates in pp (left) and PbPb (right) collisions measured in the range $|y| < 2.4$ and in the p_T range of 15–50 GeV/c. The χ^2 divided by the number of degrees of freedom (nDOF) is also given.

maximize the statistical significance of the B_s^0 meson signals. The B_s^0 signal samples are taken from simulation. The signal samples are scaled to the number of B_s^0 candidates predicted by FONLL calculations corresponding to the integrated luminosity of the analyzed data sample. This normalization is not used when performing the BDT training. The background samples for the multivariate training are taken from data sidebands of the B_s^0 meson invariant mass ($0.2 < |M_{\mu\mu KK} - M_{B_s^0,PDG}| < 0.3$ GeV/c^2), which is about 5σ away from the PDG B_s^0 mass value. The optimal selection criterion is the working point with the highest signal significance ($N_s/\sqrt{(N_s + N_b)}$, where N_s (N_b) are the expected signal (background) candidate yields from the simulated signal (data sidebands) within the mass range $|M_{\mu\mu KK} - M_{B_s^0,PDG}| < 0.08$ GeV/c^2.

The raw yields of B_s^0 mesons in pp and PbPb collisions are extracted using an extended unbinned maximum likelihood fit to the invariant mass distribution of the B_s^0 candidates in the mass range 5–6 GeV/c^2. The estimation of the statistical uncertainties of the fitted raw yields is based on the second derivatives of the negative log-likelihood function. Examples of fits to the invariant mass distributions in pp and PbPb collisions are shown in Figs. 1 and 2 for the p_T regions 7–15 and 15–50 GeV/c, respectively. The signal shape is modeled by two Gaussian functions with a common mean (which is a free parameter together with the amplitude), and different widths individually determined from MC simulations for the pp and PbPb results. The relative contribution of the two Gaussian functions to the signal yield is also fixed at the value given by the MC sample. The background is dominated by random combinations of prompt and nonprompt J/ψ candidates with extra particles and it is modeled by a first-order polynomial, as determined by studies of the inclusive J/ψ MC sample. Peaking structures that could arise from the background contamination of other B meson decays (e.g., $B^0 \to J/\psi\ K^{*0}$) were found to be negligible as a consequence of the tight selection on the mass of the ϕ candidate.

The differential cross section for B_s^0 production in $|y| < 2.4$ is computed in each p_T interval according to

$$\left.\frac{d\sigma^{B_s^0}}{dp_T}\right|_{|y|<2.4} = \left.\frac{1}{2}\frac{1}{\mathcal{B}\mathcal{L}}\frac{1}{\Delta p_T}\frac{N_{pp}^{(B_s^0+\overline{B}_s^0)}(p_T)}{\alpha_{pp}(p_T)\,\epsilon_{pp}(p_T)}\right|_{|y|<2.4}, \tag{1}$$

for pp data, and for PbPb data according to

$$\left.\frac{1}{T_{AA}}\frac{dN_{PbPb}^{B_s^0}}{dp_T}\right|_{|y|<2.4}$$

$$= \frac{1}{2}\frac{1}{\mathcal{B}\,N_{\mathrm{MB}}\,T_{\mathrm{AA}}}\frac{1}{\Delta p_{\mathrm{T}}} \times \left.\frac{N_{\mathrm{PbPb}}^{(\mathrm{B_s^0}+\overline{\mathrm{B}}_s^0)}(p_{\mathrm{T}})}{\alpha_{\mathrm{PbPb}}(p_{\mathrm{T}})\,\epsilon_{\mathrm{PbPb}}(p_{\mathrm{T}})}\right|_{|y|<2.4}. \quad (2)$$

The $N_{\mathrm{pp,PbPb}}^{(\mathrm{B_s^0}+\overline{\mathrm{B}}_s^0)}$ is the raw signal yield extracted in each p_{T} interval of width Δp_{T}, $(\alpha,\epsilon)_{\mathrm{pp,PbPb}}$ represents the corresponding acceptance times efficiency, and $\mathcal{B}$ is the branching fraction of the decay chain. For the pp cross section, $\mathcal{L}$ represents the integrated luminosity, and for the PbPb cross section, N_{MB} is the number of minimum bias events and T_{AA} is the nuclear overlap function [43]. The T_{AA} is equal to the number of NN binary collisions divided by the NN total inelastic cross section, and it can be interpreted as the NN-equivalent integrated luminosity per heavy ion collision. The T_{AA} value for inclusive PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV is (5.6 ± 0.2) mb^{-1} as estimated from an MC Glauber model [38,43]. Assuming that, in the kinematic region accessible by the present measurement, the $\mathrm{B_s^0}$ and $\overline{\mathrm{B}}_s^0$ production cross sections are equal, the factor 1/2 accounts for the fact that the yields are measured for particles and antiparticles added together, but the cross section is given for one species only.

Table 1
Summary of systematic uncertainties in percentage (%) from each source in pp and PbPb analyses.

Collision system	pp			PbPb	
p_{T} interval (GeV/c)	[7,15]	[15,20]	[20,50]	[7,15]	[15,50]
Signal modeling	2.5	0.7	0.7	4.2	3.5
Background modeling	3.4	1.6	1.6	8.7	0.68
$\mathrm{B_s^0}$ selection	15	2.6	2.6	19	8.6
$\mathrm{B_s^0}$ acceptance	1.7	1.4	1.7	1.7	1.7
$\mathrm{B_s^0}$ efficiency	6.5	0.5	0.9	7.9	3.8
MC sample size	0.8	0.8	0.5	4.9	2.1
Muon trigger, reconstruction, and identification	4.4	3.3	3.0	5.1	3.8
Hadron tracking efficiency	8	8	8	12	12
Total	19	9.4	9.3	26	16
Branching fractions			7.6		
Number of minimum bias events in PbPb data		–		2	
T_{AA}		–		+2.8/−3.4	
Integrated luminosity of pp data		2.3		–	

4. Systematic uncertainties

The cross section measurements are affected by several sources of systematic uncertainties arising from the signal extraction, corrections, $\mathcal{B}$, $\mathcal{L}$, N_{MB}, and T_{AA} determination. Unless mentioned otherwise, the same procedures were used to estimate the uncertainties for the pp and PbPb results. The uncertainty of the signal modeling is evaluated by considering four fit variations: (i) increasing/decreasing the width parameters determined from simulation by 4% (the maximum relative statistical uncertainty of the fitted width parameter among all p_{T} bins from pp and PbPb data); (ii) using a single Gaussian function; (iii) using a sum of three Gaussian functions with a common mean, and, (iv) fixing the mean of the Gaussian function to the value determined from simulation. The uncertainty in the modeling of the background shapes is also evaluated by varying the probability distribution functions used to describe the background to a higher-order polynomial and exponential function. The maximum of the signal variations and the maximum of all the background variations are propagated as systematic uncertainties. For the pp results, the systematic uncertainty due to the selection of the $\mathrm{B_s^0}$ meson candidates is estimated by comparing the BDT-obtained nominal result with the results using a cut-based method (a rectangular cut) that uses the Genetic Algorithm to determine the best cut value for each parameter [42]. The same signal and background shape parametrization are used, and the same analysis parameters are optimized as in the BDT nominal method. The significance is similar for the two methods (∼8) for the pp bins. This provides an estimate of the potential difference between different selection criteria. The full difference between the two methods is propagated as a systematic uncertainty. For the PbPb results, because of the small signal in data, in order to minimize the impact of statistical fluctuations, a different approach was taken. In this case, the $\mathrm{B_s^0}$ selection uncertainty was estimated using the pp data sample, as the full difference in the yield between the pp results with the BDT trained on the pp sample (the nominal result) and the results with the BDT trained on the PbPb sample (the selection used for the PbPb results).

The bin-by-bin systematic uncertainties associated with the acceptance correction are estimated by varying the shape of the generated $\mathrm{B_s^0}$ meson p_{T} and y spectra. For the purpose of the systematic studies only, both data and MC are split into four p_{T} and y bins. The ratio between data and simulated p_{T} spectra (including their statistical uncertainties) is used to generate pseudo-experiments ('toys'). Each toy is fit with a polynomial, which is then used to reweight the MC $\mathrm{B_s^0}$ meson p_{T} spectra. A new acceptance value is calculated for each modified shape, for each kinematic bin. The root mean square (RMS) of all acceptances determined via toys is propagated as the systematic uncertainty by choosing the maximum RMS value emerging from the p_{T} and y shape variations. Because of the small signal available, for the PbPb results the pp ratio is used to generate the toys. There is also an uncertainty assigned to account for potential bias in the efficiency calculations from the FONLL simulations of the $\mathrm{B_s^0}$ meson p_{T} shape. This uncertainty is calculated as the difference between the nominal results and those obtained by generating the PYTHIA p_{T} shape. An additional uncertainty comes from the finite size of the MC samples. This is determined by the statistical uncertainty of the simulated signal, after applying all selection criteria.

The uncertainty in the efficiency of the muon trigger, reconstruction, and identification is evaluated bin-by-bin using control samples in data [44]. A relative systematic uncertainty of 4% per hadron track in pp collisions [29] and 6% in PbPb collisions [38] is also considered, to account for the uncertainty in the track reconstruction efficiency. This uncertainty propagates to 8% and 12% for the $\mathrm{B_s^0}$ measurement in pp and PbPb, respectively. The systematic uncertainty in the cross section measurement is computed as the sum in quadrature of the different contributions mentioned above. The uncertainty in the $\mathrm{B_s^0}$ meson decay $\mathcal{B}$ is 7.6% [28]. The uncertainty for N_{MB} accounts for the inefficiency of the event selection and the trigger in selecting hadronic events [38]. The T_{AA} uncertainty is +2.8%, −3.4% [38]. In the calculations of the systematic uncertainties of the $\mathrm{B_s^0}$ meson R_{AA} and the $\mathrm{R_{AA}}$ ratio between $\mathrm{B_s^0}$ and $\mathrm{B^+}$, correlated uncertainties from the track and muon reconstruction and identification are partially canceled.

The values for each systematic uncertainty source are listed in Table 1.

5. Results

In Fig. 3 and in the top panel of Fig. 4, the p_{T}-differential production cross sections in pp and PbPb collisions measured in the interval $|y| < 2.4$ are presented. The pp results are compared to the predictions of FONLL calculations [26]. The FONLL reference cross section is obtained by multiplying the FONLL total b quark production [24–26] by the world-average production fraction of $\mathrm{B_s^0}$ of 10.3% [28]. The $\mathrm{B_s^0}$ FONLL prediction is consistent with the measured $\mathrm{B_s^0}$ pp spectrum within the uncertainties. The measured

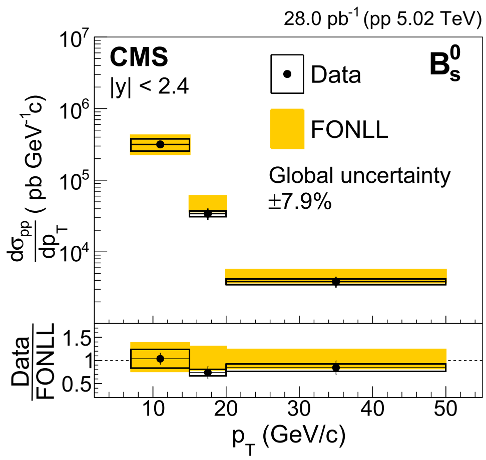

Fig. 3. The p_T-differential production cross section of B_s^0 in pp collisions at $\sqrt{s} = 5.02$ TeV in three p_T intervals from 7 to 50 GeV/c. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty, listed in the legend and not included in the point-to-point uncertainties, comprises the uncertainties in the integrated luminosity measurement and in the branching fraction $\mathcal{B}$. The pp cross section is compared to FONLL calculations [26] represented by the colored yellow boxes with the heights indicating the theoretical uncertainty.

spectrum has a smaller uncertainty than that of the FONLL calculation.

The nuclear modification factor R_{AA}, shown in Fig. 4, is computed as:

$$R_{AA}(p_T) = \frac{1}{T_{AA}} \frac{dN_{PbPb}^{B_s^0}}{dp_T} \bigg/ \frac{d\sigma_{pp}^{B_s^0}}{dp_T}. \tag{3}$$

The B_s^0 meson R_{AA} is $1.5 \pm 0.6(\text{stat}) \pm 0.5(\text{syst})$ for 7–15 GeV/c, and $0.87 \pm 0.30(\text{stat}) \pm 0.17(\text{syst})$ for 15–50 GeV/c, respectively. In the bottom panel of Fig. 4, the R_{AA} of B^+ mesons from a previous measurement [27] is also shown. Compared to the B^+ mesons, there is an indication of an enhancement for B_s^0 mesons, which would be the expectation in the presence of a contribution from beauty recombination with strange quarks in heavy ion collisions. However, the B_s^0 R_{AA} values are compatible with unity and their large uncertainties do not exclude a significant suppression. The p_T dependence of R_{AA} is compared to the B_s^0 prediction of a perturbative QCD based model that includes both collisional and radiative energy loss, (CUJET3.0) [45–47], and a transport model based on a Langevin equation that includes collisional energy loss and heavy quark diffusion in the medium, (TAMU) [17,48]. The difference between the two models below $p_T \sim 15$ GeV reflects the contribution from recombination processes, which are included in the TAMU but not in the CUJET3.0 model. The results measured for $p_T > 7$ GeV/c have the power to disentangle the two models, albeit after an increase in precision, which can be achieved with a bigger data sample.

To further quantify the significance of a possible enhancement of the B_s^0/B^+ ratio in PbPb with respect to pp collisions, the ratio between the B_s^0 and the B^+ R_{AA} is also calculated, canceling the systematic uncertainty sources that are common to both measurements (acceptance, tracking efficiency, and muon-related). The B^+ R_{AA} with a wider p_T binning (15–50 GeV/c) is obtained by a B^+ yield weighted average of the results from three p_T bins (15–20, 20–30 and 30–50 GeV/c) presented in previous work [27]. The result is shown in Fig. 5. The ratio is $4.0 \pm 1.8(\text{stat}) \pm 1.3(\text{syst})$ for 7–15 GeV/c, and $1.8 \pm 0.7(\text{stat}) \pm 0.3(\text{syst})$ for 15–50 GeV/c, respectively. Assuming a Gaussian distribution with mean and width equal to that of the R_{AA} ratio and its uncertainty (including statistical and systematic components added in quadrature), the hypothesis of the ratio values being consistent with unity (no enhancement) is tested with a χ^2 test. The resulting p-values are 18% and 28% for 7–15 and 15–50 GeV/c, respectively. This shows that, with a p-value cutoff of 5%, the scenario of no enhancement cannot be rejected. This analysis demonstrates the capability of performing a fully reconstructed B_s^0 measurement in PbPb collisions with the CMS detector.

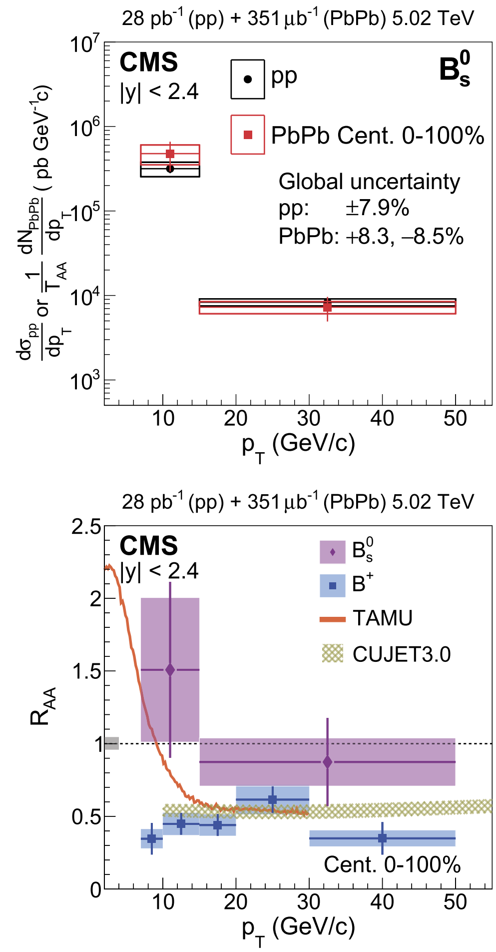

Fig. 4. (top) The p_T-differential production cross section of B_s^0 mesons in pp collisions and the p_T-differential corrected yield of B_s^0 mesons scaled by T_{AA} in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in two p_T intervals from 7 to 50 GeV/c. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The global systematic uncertainty comprises the uncertainties in T_{AA}, N_{MB}, and $\mathcal{B}$. (bottom) The nuclear modification factor R_{AA} of B_s^0 measured in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from 7 to 50 GeV/c. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The B^+ R_{AA} measurement [27] is also shown for comparison. The global systematic uncertainty, represented by the grey box at $R_{AA} = 1$, comprises the uncertainties in the integrated luminosity measurement and T_{AA} value. Two B_s^0 theoretical calculations are also shown for comparison: TAMU [17,48] and CUJET3.0 [45–47]. The line width of the theoretical calculation from Refs. [17,48] represents the size of its statistical uncertainty.

6. Summary

The first measurement of the differential production cross section of B_s^0 mesons (including both charge conjugates) in both pp and PbPb collisions at a center-of-mass energy of 5.02 TeV per nucleon pair is presented. The B_s^0 and $\overline{B}_s^0$ mesons are studied with the CMS detector at the LHC in the rapidity range $|y| < 2.4$ via the reconstruction of one of their exclusive hadronic decay channels, $B_s^0 \to J/\psi\phi \to \mu^+\mu^-K^+K^-$. The nuclear modification factor R_{AA} of B_s^0 is measured in the transverse momentum range from

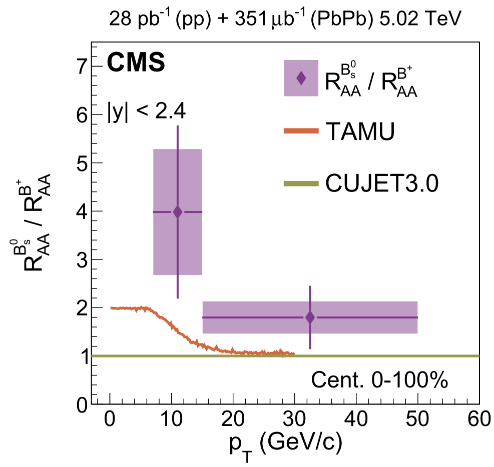

Fig. 5. The nuclear modification factor R_{AA} ratio between B_s^0 and B^+ measured in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV from 7 to 50 GeV/c. Two B_s^0 theoretical calculations are also shown for comparison: TAMU [17,48], and CUJET3.0 [45–47].

7 to 50 GeV/c, inclusively for 0–100% event centrality. A hint of an enhancement of the B_s^0/B^+ ratio in PbPb with respect to pp collisions is seen. More precise measurements of the B_s^0 and $B^\pm$ mesons R_{AA} with the upcoming high-luminosity LHC heavy ion runs could provide further constraints on the relevance of recombination, a marker of deconfined matter, for beauty hadron production, and unambiguous information about the mechanisms of beauty hadronization in heavy ion collisions.

Acknowledgements

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MOST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, ROSATOM, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MoSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the A.G. Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the "Excellence of Science - EOS" - be.h project n. 30820817; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület ("Momentum") Programme and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIA research grants 123842, 123959, 124845, 124850 and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, European Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).

References

[1] É.V. Shuryak, Theory of hadronic plasma, Sov. Phys. JETP 47 (1978) 212, http://www.jetp.ac.ru/cgi-bin/e/index/e/47/2/p212?a=list.
[2] J.C. Collins, M.J. Perry, Superdense matter: neutrons or asymptotically free quarks? Phys. Rev. Lett. 34 (1975) 1353, https://doi.org/10.1103/PhysRevLett.34.1353.
[3] F. Karsch, E. Laermann, Thermodynamics and in-medium hadron properties from lattice QCD, in: R. Hwa (Ed.), Quark-Gluon Plasma III, 2003, arXiv:hep-lat/0305025.
[4] J.D. Bjorken, Energy loss of energetic partons in quark-gluon plasma: possible extinction of high p_T jets in hadron-hadron collisions, Fermilab PUB 82-059-THY, http://lss.fnal.gov/archive/1982/pub/Pub-82-059-T.pdf, 1982.
[5] R. Baier, D. Schiff, B.G. Zakharov, Energy loss in perturbative QCD, Annu. Rev. Nucl. Part. Sci. 50 (2000) 37, https://doi.org/10.1146/annurev.nucl.50.1.37, arXiv:hep-ph/0002198.
[6] CMS Collaboration, Observation and studies of jet quenching in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. C 84 (2011) 024906, https://doi.org/10.1103/PhysRevC.84.024906, arXiv:1102.1957.
[7] ATLAS Collaboration, Observation of a centrality-dependent dijet asymmetry in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector at the LHC, Phys. Rev. Lett. 105 (2010) 252303, https://doi.org/10.1103/PhysRevLett.105.252303, arXiv:1011.6182.
[8] A. Andronic, et al., Heavy-flavour and quarkonium production in the LHC era: from proton-proton to heavy-ion collisions, Eur. Phys. J. C 76 (2016) 107, https://doi.org/10.1140/epjc/s10052-015-3819-5, arXiv:1506.03981.
[9] J. Rafelski, B. Müller, Strangeness production in the quark - gluon plasma, Phys. Rev. Lett. 48 (1982) 1066, https://doi.org/10.1103/PhysRevLett.48.1066, Erratum: https://doi.org/10.1103/PhysRevLett.56.2334.
[10] G. Agakishiev, et al., STAR Collaboration, Strangeness enhancement in Cu+Cu and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. Lett. 108 (2012) 072301, https://doi.org/10.1103/PhysRevLett.108.072301, arXiv:1107.2955.
[11] B.I. Abelev, et al., STAR Collaboration, Energy and system size dependence of phi meson production in Cu+Cu and Au+Au collisions, Phys. Lett. B 673 (2009) 183, https://doi.org/10.1016/j.physletb.2009.02.037, arXiv:0810.4979.
[12] I.C. Arsene, et al., BRAHMS Collaboration, Kaon and pion production in central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV, Phys. Lett. B 687 (2010) 36, https://doi.org/10.1016/j.physletb.2010.02.078, arXiv:0911.2586.
[13] L. Adamczyk, et al., STAR Collaboration, Collision energy dependence of moments of net-kaon multiplicity distributions at RHIC, Phys. Lett. B 785 (2018) 551, https://doi.org/10.1016/j.physletb.2018.07.066, arXiv:1709.00773.
[14] A. Adare, et al., PHENIX Collaboration, ϕ meson production in the forward/backward rapidity region in Cu+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, Phys. Rev. C 93 (2016) 024904, https://doi.org/10.1103/PhysRevC.93.024904, arXiv:1509.06337.
[15] ALICE Collaboration, Enhanced production of multi-strange hadrons in high-multiplicity proton-proton collisions, Nat. Phys. 13 (2017) 535, https://doi.org/10.1038/nphys4111, arXiv:1606.07424.

[16] ALICE Collaboration, K_S^0 and Λ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, Phys. Rev. Lett. 111 (2013) 222301, https://doi.org/10.1103/PhysRevLett.111.222301, arXiv:1307.5530.
[17] M. He, R.J. Fries, R. Rapp, Heavy flavor at the large hadron collider in a strong coupling approach, Phys. Lett. B 735 (2014) 445, https://doi.org/10.1016/j.physletb.2014.05.050, arXiv:1401.3817.
[18] D. Molnar, S.A. Voloshin, Elliptic flow at large transverse momenta from quark coalescence, Phys. Rev. Lett. 91 (2003) 092301, https://doi.org/10.1103/PhysRevLett.91.092301, arXiv:nucl-th/0302014.
[19] V. Greco, C.M. Ko, P. Levai, Parton coalescence at RHIC, Phys. Rev. C 68 (2003) 034904, https://doi.org/10.1103/PhysRevC.68.034904, arXiv:nucl-th/0305024.
[20] V. Greco, C.M. Ko, R. Rapp, Quark coalescence for charmed mesons in ultrarelativistic heavy ion collisions, Phys. Lett. B 595 (2004) 202, https://doi.org/10.1016/j.physletb.2004.06.064, arXiv:nucl-th/0312100.
[21] ALICE Collaboration, Measurement of D^0, D^+, D^{*+} and D_s^+ production in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, J. High Energy Phys. 10 (2018) 174, https://doi.org/10.1007/JHEP10(2018)174, arXiv:1804.09083.
[22] CMS Collaboration, Measurement of the B_s^0 production cross section with $B_s^0 \to J/\psi\phi$ decays in pp collisions at $\sqrt{s} = 7$ TeV, Phys. Rev. D 84 (2011) 052008, https://doi.org/10.1103/PhysRevD.84.052008, arXiv:1106.4048.
[23] CMS Collaboration, Study of B meson production in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using exclusive hadronic decays, Phys. Rev. Lett. 116 (2016) 032301, https://doi.org/10.1103/PhysRevLett.116.032301, arXiv:1508.06678.
[24] M. Cacciari, M. Greco, P. Nason, The p_T spectrum in heavy-flavour hadroproduction, J. High Energy Phys. 05 (1998) 007, https://doi.org/10.1088/1126-6708/1998/05/007, arXiv:hep-ph/9803400.
[25] M. Cacciari, P. Nason, Charm cross sections for the Tevatron Run II, J. High Energy Phys. 09 (2003) 006, https://doi.org/10.1088/1126-6708/2003/09/006, arXiv:hep-ph/0306212.
[26] M. Cacciari, S. Frixione, N. Houdeau, M.L. Mangano, P. Nason, G. Ridolfi, Theoretical predictions for charm and bottom production at the LHC, J. High Energy Phys. 10 (2012) 137, https://doi.org/10.1007/JHEP10(2012)137, arXiv:1205.6344.
[27] CMS Collaboration, Measurement of the $B^{\pm}$ meson nuclear modification factor in Pb-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, Phys. Rev. Lett. 119 (2017) 152301, https://doi.org/10.1103/PhysRevLett.119.152301, arXiv:1705.04727.
[28] C. Patrignani, et al., Particle Data Group, Review of particle physics, Chin. Phys. C 40 (2016) 100001, https://doi.org/10.1088/1674-1137/40/10/100001.
[29] CMS Collaboration, Description and performance of track and primary-vertex reconstruction with the CMS tracker, J. Instrum. 9 (2014) P10009, https://doi.org/10.1088/1748-0221/9/10/P10009, arXiv:1405.6569.
[30] CMS Collaboration, Performance of CMS muon reconstruction in pp collision events at $\sqrt{s} = 7$ TeV, J. Instrum. 7 (2012) P10002, https://doi.org/10.1088/1748-0221/7/10/P10002, arXiv:1206.4071.
[31] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, https://doi.org/10.1088/1748-0221/3/08/S08004.
[32] T. Sjöstrand, S. Ask, J.R. Christiansen, R. Corke, N. Desai, P. Ilten, S. Mrenna, S. Prestel, C.O. Rasmussen, P.Z. Skands, An introduction to PYTHIA 8.2, Comput. Phys. Commun. 191 (2015) 159, https://doi.org/10.1016/j.cpc.2015.01.024, arXiv:1410.3012.
[33] CMS Collaboration, Event generator tunes obtained from underlying event and multiparton scattering measurements, Eur. Phys. J. C 76 (2016), https://doi.org/10.1140/epjc/s10052-016-3988-x, arXiv:1512.00815.
[34] J. Allison, et al., Recent developments in Geant4, Nucl. Instrum. Methods A 835 (2016) 186, https://doi.org/10.1016/j.nima.2016.06.125.
[35] D.J. Lange, The EvtGen particle decay simulation package, Nucl. Instrum. Methods A 462 (2001) 152, https://doi.org/10.1016/S0168-9002(01)00089-4.
[36] E. Barberio, B. van Eijk, Z. Was, PHOTOS: a universal Monte Carlo for QED radiative corrections in decays, Comput. Phys. Commun. 66 (1991) 115, https://doi.org/10.1016/0010-4655(91)90012-A.
[37] I.P. Lokhtin, A.M. Snigirev, A model of jet quenching in ultrarelativistic heavy ion collisions and high-p_T hadron spectra at RHIC, Eur. Phys. J. C 45 (2006) 211, https://doi.org/10.1140/epjc/s2005-02426-3, arXiv:hep-ph/0506189.
[38] CMS Collaboration, Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, J. High Energy Phys. 04 (2017) 039, https://doi.org/10.1007/JHEP04(2017)039, arXiv:1611.01664.
[39] CMS Collaboration, Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.76 TeV, J. High Energy Phys. 02 (2010) 041, https://doi.org/10.1007/JHEP02(2010)041, arXiv:1002.0621.
[40] CMS Collaboration, CMS luminosity calibration for the p p reference run at $\sqrt{s} = 5.02$ TeV, CMS Physics Analysis Summary CMS-PAS-LUM-16-001, 2016, https://cds.cern.ch/record/2235781.
[41] Particle Data Group, M. Tanabashi, et al., Review of particle physics, Phys. Rev. D 98 (2018) 030001, https://doi.org/10.1103/PhysRevD.98.030001.
[42] H. Voss, A. Höcker, J. Stelzer, F. Tegenfeldt, TMVA – the toolkit for multivariate data analysis, in: XIth International Workshop on Advanced Computing and Analysis Techniques in Physics Research (ACAT), 2009, p. 40, http://pos.sissa.it/archive/conferences/050/040/ACAT_040.pdf, arXiv:physics/0703039.
[43] M.L. Miller, K. Reygers, S.J. Sanders, P. Steinberg, Glauber modeling in high-energy nuclear collisions, Annu. Rev. Nucl. Part. Sci. 57 (2007) 205, https://doi.org/10.1146/annurev.nucl.57.090506.123020, arXiv:nucl-ex/0701025.
[44] CMS Collaboration, Measurements of inclusive W and Z cross sections in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 01 (2011) 080, https://doi.org/10.1007/JHEP01(2011)080, arXiv:1012.2466.
[45] J. Xu, J. Liao, M. Gyulassy, Bridging soft-hard transport properties of quark-gluon plasmas with CUJET3.0, J. High Energy Phys. 02 (2016) 169, https://doi.org/10.1007/JHEP02(2016)169, arXiv:1508.00552.
[46] J. Xu, J. Liao, M. Gyulassy, Consistency of perfect fluidity and jet quenching in semi-quark-gluon monopole plasmas, Chin. Phys. Lett. 32 (2015) 092501, https://doi.org/10.1088/0256-307X/32/9/092501, arXiv:1411.3673.
[47] J. Xu, A. Buzzatti, M. Gyulassy, Azimuthal jet flavor tomography with CUJET2.0 of nuclear collisions at RHIC and LHC, J. High Energy Phys. 08 (2014) 063, https://doi.org/10.1007/JHEP08(2014)063, arXiv:1402.2956.
[48] M. He, R.J. Fries, R. Rapp, Heavy-quark diffusion and hadronization in quark-gluon plasma, Phys. Rev. C 86 (2012) 014903, https://doi.org/10.1103/PhysRevC.86.014903, arXiv:1106.6006.

The CMS Collaboration

A.M. Sirunyan, A. Tumasyan

Yerevan Physics Institute, Yerevan, Armenia

W. Adam, F. Ambrogi, E. Asilar, T. Bergauer, J. Brandstetter, M. Dragicevic, J. Erö, A. Escalante Del Valle, M. Flechl, R. Frühwirth [1], V.M. Ghete, J. Hrubec, M. Jeitler [1], N. Krammer, I. Krätschmer, D. Liko, T. Madlener, I. Mikulec, N. Rad, H. Rohringer, J. Schieck [1], R. Schöfbeck, M. Spanring, D. Spitzbart, A. Taurok, W. Waltenberger, J. Wittmann, C.-E. Wulz [1], M. Zarucki

Institut für Hochenergiephysik, Wien, Austria

V. Chekhovsky, V. Mossolov, J. Suarez Gonzalez

Institute for Nuclear Problems, Minsk, Belarus

E.A. De Wolf, D. Di Croce, X. Janssen, J. Lauwers, M. Pieters, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Universiteit Antwerpen, Antwerpen, Belgium

S. Abu Zeid, F. Blekman, J. D'Hondt, I. De Bruyn, J. De Clercq, K. Deroover, G. Flouris, D. Lontkovskyi, S. Lowette, I. Marchesini, S. Moortgat, L. Moreels, Q. Python, K. Skovpen, S. Tavernier, W. Van Doninck, P. Van Mulders, I. Van Parijs

Vrije Universiteit Brussel, Brussel, Belgium

D. Beghin, B. Bilin, H. Brun, B. Clerbaux, G. De Lentdecker, H. Delannoy, B. Dorney, G. Fasanella, L. Favart, R. Goldouzian, A. Grebenyuk, A.K. Kalsi, T. Lenzi, J. Luetic, N. Postiau, E. Starling, L. Thomas, C. Vander Velde, P. Vanlaer, D. Vannerom, Q. Wang

Université Libre de Bruxelles, Bruxelles, Belgium

T. Cornelis, D. Dobur, A. Fagot, M. Gul, I. Khvastunov [2], D. Poyraz, C. Roskas, D. Trocino, M. Tytgat, W. Verbeke, B. Vermassen, M. Vit, N. Zaganidis

Ghent University, Ghent, Belgium

H. Bakhshiansohi, O. Bondu, S. Brochet, G. Bruno, C. Caputo, P. David, C. Delaere, M. Delcourt, B. Francois, A. Giammanco, G. Krintiras, V. Lemaitre, A. Magitteri, A. Mertens, M. Musich, K. Piotrzkowski, A. Saggio, M. Vidal Marono, S. Wertz, J. Zobec

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

F.L. Alves, G.A. Alves, M. Correa Martins Junior, G. Correia Silva, C. Hensel, A. Moraes, M.E. Pol, P. Rebello Teles

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

E. Belchior Batista Das Chagas, W. Carvalho, J. Chinellato [3], E. Coelho, E.M. Da Costa, G.G. Da Silveira [4], D. De Jesus Damiao, C. De Oliveira Martins, S. Fonseca De Souza, H. Malbouisson, D. Matos Figueiredo, M. Melo De Almeida, C. Mora Herrera, L. Mundim, H. Nogima, W.L. Prado Da Silva, L.J. Sanchez Rosas, A. Santoro, A. Sznajder, M. Thiel, E.J. Tonelli Manganote [3], F. Torres Da Silva De Araujo, A. Vilela Pereira

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

S. Ahuja [a], C.A. Bernardes [a], L. Calligaris [a], T.R. Fernandez Perez Tomei [a], E.M. Gregores [b], P.G. Mercadante [b], S.F. Novaes [a], Sandra Padula [a]

[a] *Universidade Estadual Paulista, São Paulo, Brazil*
[b] *Universidade Federal do ABC, São Paulo, Brazil*

A. Aleksandrov, R. Hadjiiska, P. Iaydjiev, A. Marinov, M. Misheva, M. Rodozov, M. Shopova, G. Sultanov

Institute for Nuclear Research and Nuclear Energy, Bulgarian Academy of Sciences, Sofia, Bulgaria

A. Dimitrov, L. Litov, B. Pavlov, P. Petkov

University of Sofia, Sofia, Bulgaria

W. Fang [5], X. Gao [5], L. Yuan

Beihang University, Beijing, China

M. Ahmad, J.G. Bian, G.M. Chen, H.S. Chen, M. Chen, Y. Chen, C.H. Jiang, D. Leggat, H. Liao, Z. Liu, F. Romeo, S.M. Shaheen [6], A. Spiezia, J. Tao, Z. Wang, E. Yazgan, H. Zhang, S. Zhang [6], J. Zhao

Institute of High Energy Physics, Beijing, China

Y. Ban, G. Chen, A. Levin, J. Li, L. Li, Q. Li, Y. Mao, S.J. Qian, D. Wang, Z. Xu

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing, China

Y. Wang

Tsinghua University, Beijing, China

C. Avila, A. Cabrera, C.A. Carrillo Montoya, L.F. Chaparro Sierra, C. Florez, C.F. González Hernández, M.A. Segura Delgado

Universidad de Los Andes, Bogota, Colombia

B. Courbon, N. Godinovic, D. Lelas, I. Puljak, T. Sculac

University of Split, Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, Split, Croatia

Z. Antunovic, M. Kovac

University of Split, Faculty of Science, Split, Croatia

V. Brigljevic, D. Ferencek, K. Kadija, B. Mesic, A. Starodumov [7], T. Susa

Institute Rudjer Boskovic, Zagreb, Croatia

M.W. Ather, A. Attikis, M. Kolosova, G. Mavromanolakis, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis, H. Rykaczewski

University of Cyprus, Nicosia, Cyprus

M. Finger [8], M. Finger Jr. [8]

Charles University, Prague, Czech Republic

E. Ayala

Escuela Politecnica Nacional, Quito, Ecuador

E. Carrera Jarrin

Universidad San Francisco de Quito, Quito, Ecuador

A. Ellithi Kamel [9], M.A. Mahmoud [10,11], Y. Mohammed [10]

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

S. Bhowmik, A. Carvalho Antunes De Oliveira, R.K. Dewanjee, K. Ehataht, M. Kadastik, M. Raidal, C. Veelken

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

P. Eerola, H. Kirschenmann, J. Pekkanen, M. Voutilainen

Department of Physics, University of Helsinki, Helsinki, Finland

J. Havukainen, J.K. Heikkilä, T. Järvinen, V. Karimäki, R. Kinnunen, T. Lampén, K. Lassila-Perini, S. Laurila, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, H. Siikonen, E. Tuominen, J. Tuominiemi

Helsinki Institute of Physics, Helsinki, Finland

T. Tuuva

Lappeenranta University of Technology, Lappeenranta, Finland

M. Besancon, F. Couderc, M. Dejardin, D. Denegri, J.L. Faure, F. Ferri, S. Ganjour, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, C. Leloup, E. Locci, J. Malcles, G. Negro, J. Rander, A. Rosowsky, M.Ö. Sahin, M. Titov

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

A. Abdulsalam [12], C. Amendola, I. Antropov, F. Beaudette, P. Busson, C. Charlot, R. Granier de Cassagnac, I. Kucher, A. Lobanov, J. Martin Blanco, C. Martin Perez, M. Nguyen, C. Ochando, G. Ortona, P. Paganini, P. Pigard, J. Rembser, R. Salerno, J.B. Sauvan, Y. Sirois, A.G. Stahl Leiton, A. Zabi, A. Zghiche

Laboratoire Leprince-Ringuet, Ecole polytechnique, CNRS/IN2P3, Université Paris-Saclay, Palaiseau, France

J.-L. Agram [13], J. Andrea, D. Bloch, J.-M. Brom, E.C. Chabert, V. Cherepanov, C. Collard, E. Conte [13], J.-C. Fontaine [13], D. Gelé, U. Goerlach, M. Jansová, A.-C. Le Bihan, N. Tonon, P. Van Hove

Université de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

S. Gadrat

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules, CNRS/IN2P3, Villeurbanne, France

S. Beauceron, C. Bernet, G. Boudoul, N. Chanon, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, L. Finco, S. Gascon, M. Gouzevitch, G. Grenier, B. Ille, F. Lagarde, I.B. Laktineh, H. Lattaud, M. Lethuillier, L. Mirabito, S. Perries, A. Popov [14], V. Sordini, G. Touquet, M. Vander Donckt, S. Viret

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

T. Toriashvili [15]

Georgian Technical University, Tbilisi, Georgia

I. Bagaturia [16]

Tbilisi State University, Tbilisi, Georgia

C. Autermann, L. Feld, M.K. Kiesel, K. Klein, M. Lipinski, M. Preuten, M.P. Rauch, C. Schomakers, J. Schulz, M. Teroerde, B. Wittmer, V. Zhukov [14]

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

A. Albert, D. Duchardt, M. Erdmann, S. Erdweg, T. Esch, R. Fischer, S. Ghosh, A. Güth, T. Hebbeker, C. Heidemann, K. Hoepfner, H. Keller, L. Mastrolorenzo, M. Merschmeyer, A. Meyer, P. Millet, S. Mukherjee, T. Pook, M. Radziej, H. Reithler, M. Rieger, A. Schmidt, D. Teyssier, S. Thüer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

G. Flügge, O. Hlushchenko, T. Kress, A. Künsken, T. Müller, A. Nehrkorn, A. Nowack, C. Pistone, O. Pooth, D. Roy, H. Sert, A. Stahl [17]

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Aldaya Martin, T. Arndt, C. Asawatangtrakuldee, I. Babounikau, K. Beernaert, O. Behnke, U. Behrens, A. Bermúdez Martínez, D. Bertsche, A.A. Bin Anuar, K. Borras [18], V. Botta, A. Campbell, P. Connor, C. Contreras-Campana, V. Danilov, A. De Wit, M.M. Defranchis, C. Diez Pardos, D. Domínguez Damiani, G. Eckerlin, T. Eichhorn, A. Elwood, E. Eren, E. Gallo [19], A. Geiser, A. Grohsjean, M. Guthoff, M. Haranko, A. Harb, J. Hauk, H. Jung, M. Kasemann, J. Keaveney, C. Kleinwort, J. Knolle, D. Krücker, W. Lange, A. Lelek, T. Lenz, J. Leonard, K. Lipka, W. Lohmann [20], R. Mankel, I.-A. Melzer-Pellmann, A.B. Meyer, M. Meyer, M. Missiroli, G. Mittag, J. Mnich, V. Myronenko, S.K. Pflitsch, D. Pitzl, A. Raspereza, M. Savitskyi, P. Saxena, P. Schütze, C. Schwanenberger, R. Shevchenko, A. Singh, H. Tholen, O. Turkot, A. Vagnerini, G.P. Van Onsem, R. Walsh, Y. Wen, K. Wichmann, C. Wissing, O. Zenaiev

Deutsches Elektronen-Synchrotron, Hamburg, Germany

R. Aggleton, S. Bein, L. Benato, A. Benecke, V. Blobel, T. Dreyer, E. Garutti, D. Gonzalez, P. Gunnellini, J. Haller, A. Hinzmann, A. Karavdina, G. Kasieczka, R. Klanner, R. Kogler, N. Kovalchuk, S. Kurz, V. Kutzner, J. Lange, D. Marconi, J. Multhaup, M. Niedziela, C.E.N. Niemeyer, D. Nowatschin, A. Perieanu,

A. Reimers, O. Rieger, C. Scharf, P. Schleper, S. Schumann, J. Schwandt, J. Sonneveld, H. Stadie, G. Steinbrück, F.M. Stober, M. Stöver, A. Vanhoefer, B. Vormwald, I. Zoi

University of Hamburg, Hamburg, Germany

M. Akbiyik, C. Barth, M. Baselga, S. Baur, E. Butz, R. Caspart, T. Chwalek, F. Colombo, W. De Boer, A. Dierlamm, K. El Morabit, N. Faltermann, B. Freund, M. Giffels, M.A. Harrendorf, F. Hartmann [17], S.M. Heindl, U. Husemann, F. Kassel [17], I. Katkov [14], S. Kudella, H. Mildner, S. Mitra, M.U. Mozer, Th. Müller, M. Plagge, G. Quast, K. Rabbertz, M. Schröder, I. Shvetsov, G. Sieber, H.J. Simonis, R. Ulrich, S. Wayand, M. Weber, T. Weiler, S. Williamson, C. Wöhrmann, R. Wolf

Karlsruher Institut fuer Technologie, Karlsruhe, Germany

G. Anagnostou, G. Daskalakis, T. Geralis, A. Kyriakis, D. Loukas, G. Paspalaki, I. Topsis-Giotis

Institute of Nuclear and Particle Physics (INPP), NCSR Demokritos, Aghia Paraskevi, Greece

G. Karathanasis, S. Kesisoglou, P. Kontaxakis, A. Panagiotou, I. Papavergou, N. Saoulidou, E. Tziaferi, K. Vellidis

National and Kapodistrian University of Athens, Athens, Greece

K. Kousouris, I. Papakrivopoulos, G. Tsipolitis

National Technical University of Athens, Athens, Greece

I. Evangelou, C. Foudas, P. Gianneios, P. Katsoulis, P. Kokkas, S. Mallios, N. Manthos, I. Papadopoulos, E. Paradas, J. Strologas, F.A. Triantis, D. Tsitsonis

University of Ioánnina, Ioánnina, Greece

M. Bartók [21], M. Csanad, N. Filipovic, P. Major, M.I. Nagy, G. Pasztor, O. Surányi, G.I. Veres

MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary

G. Bencze, C. Hajdu, D. Horvath [22], Á. Hunyadi, F. Sikler, T.Á. Vámi, V. Veszpremi, G. Vesztergombi [†]

Wigner Research Centre for Physics, Budapest, Hungary

N. Beni, S. Czellar, J. Karancsi [23], A. Makovec, J. Molnar, Z. Szillasi

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Institute of Physics, University of Debrecen, Debrecen, Hungary

S. Choudhury, J.R. Komaragiri, P.C. Tiwari

Indian Institute of Science (IISc), Bangalore, India

S. Bahinipati [24], C. Kar, P. Mal, K. Mandal, A. Nayak [25], D.K. Sahoo [24], S.K. Swain

National Institute of Science Education and Research, HBNI, Bhubaneswar, India

S. Bansal, S.B. Beri, V. Bhatnagar, S. Chauhan, R. Chawla, N. Dhingra, R. Gupta, A. Kaur, M. Kaur, S. Kaur, R. Kumar, P. Kumari, M. Lohan, A. Mehta, K. Sandeep, S. Sharma, J.B. Singh, A.K. Virdi, G. Walia

Panjab University, Chandigarh, India

A. Bhardwaj, B.C. Choudhary, R.B. Garg, M. Gola, S. Keshri, Ashok Kumar, S. Malhotra, M. Naimuddin, P. Priyanka, K. Ranjan, Aashaq Shah, R. Sharma

University of Delhi, Delhi, India

R. Bhardwaj [26], M. Bharti [26], R. Bhattacharya, S. Bhattacharya, U. Bhawandeep [26], D. Bhowmik, S. Dey, S. Dutt [26], S. Dutta, S. Ghosh, K. Mondal, S. Nandan, A. Purohit, P.K. Rout, A. Roy, S. Roy Chowdhury, G. Saha, S. Sarkar, M. Sharan, B. Singh [26], S. Thakur [26]

Saha Institute of Nuclear Physics, HBNI, Kolkata, India

P.K. Behera

Indian Institute of Technology Madras, Madras, India

R. Chudasama, D. Dutta, V. Jha, V. Kumar, P.K. Netrakanti, L.M. Pant, P. Shukla

Bhabha Atomic Research Centre, Mumbai, India

T. Aziz, M.A. Bhat, S. Dugad, G.B. Mohanty, N. Sur, B. Sutar, R.K. Verma

Tata Institute of Fundamental Research-A, Mumbai, India

S. Banerjee, S. Bhattacharya, S. Chatterjee, P. Das, M. Guchait, Sa. Jain, S. Karmakar, S. Kumar, M. Maity [27], G. Majumder, K. Mazumdar, N. Sahoo, T. Sarkar [27]

Tata Institute of Fundamental Research-B, Mumbai, India

S. Chauhan, S. Dube, V. Hegde, A. Kapoor, K. Kothekar, S. Pandey, A. Rane, S. Sharma

Indian Institute of Science Education and Research (IISER), Pune, India

S. Chenarani [28], E. Eskandari Tadavani, S.M. Etesami [28], M. Khakzad, M. Mohammadi Najafabadi, M. Naseri, F. Rezaei Hosseinabadi, B. Safarzadeh [29], M. Zeinali

Institute for Research in Fundamental Sciences (IPM), Tehran, Iran

M. Felcini, M. Grunewald

University College Dublin, Dublin, Ireland

M. Abbrescia [a,b], C. Calabria [a,b], A. Colaleo [a], D. Creanza [a,c], L. Cristella [a,b], N. De Filippis [a,c], M. De Palma [a,b], A. Di Florio [a,b], F. Errico [a,b], L. Fiore [a], A. Gelmi [a,b], G. Iaselli [a,c], M. Ince [a,b], S. Lezki [a,b], G. Maggi [a,c], M. Maggi [a], G. Miniello [a,b], S. My [a,b], S. Nuzzo [a,b], A. Pompili [a,b], G. Pugliese [a,c], R. Radogna [a], A. Ranieri [a], G. Selvaggi [a,b], A. Sharma [a], L. Silvestris [a], R. Venditti [a], P. Verwilligen [a], G. Zito [a]

[a] *INFN Sezione di Bari, Bari, Italy*
[b] *Università di Bari, Bari, Italy*
[c] *Politecnico di Bari, Bari, Italy*

G. Abbiendi [a], C. Battilana [a,b], D. Bonacorsi [a,b], L. Borgonovi [a,b], S. Braibant-Giacomelli [a,b], R. Campanini [a,b], P. Capiluppi [a,b], A. Castro [a,b], F.R. Cavallo [a], S.S. Chhibra [a,b], C. Ciocca [a], G. Codispoti [a,b], M. Cuffiani [a,b], G.M. Dallavalle [a], F. Fabbri [a], A. Fanfani [a,b], E. Fontanesi, P. Giacomelli [a], C. Grandi [a], L. Guiducci [a,b], S. Lo Meo [a], S. Marcellini [a], G. Masetti [a], A. Montanari [a], F.L. Navarria [a,b], A. Perrotta [a], F. Primavera [a,b,17], A.M. Rossi [a,b], T. Rovelli [a,b], G.P. Siroli [a,b], N. Tosi [a]

[a] *INFN Sezione di Bologna, Bologna, Italy*
[b] *Università di Bologna, Bologna, Italy*

S. Albergo [a,b], A. Di Mattia [a], R. Potenza [a,b], A. Tricomi [a,b], C. Tuve [a,b]

[a] *INFN Sezione di Catania, Catania, Italy*
[b] *Università di Catania, Catania, Italy*

G. Barbagli [a], K. Chatterjee [a,b], V. Ciulli [a,b], C. Civinini [a], R. D'Alessandro [a,b], E. Focardi [a,b], G. Latino, P. Lenzi [a,b], M. Meschini [a], S. Paoletti [a], L. Russo [a,30], G. Sguazzoni [a], D. Strom [a], L. Viliani [a]

[a] *INFN Sezione di Firenze, Firenze, Italy*
[b] *Università di Firenze, Firenze, Italy*

L. Benussi, S. Bianco, F. Fabbri, D. Piccolo

INFN Laboratori Nazionali di Frascati, Frascati, Italy

F. Ferro [a], F. Ravera [a,b], E. Robutti [a], S. Tosi [a,b]

[a] *INFN Sezione di Genova, Genova, Italy*
[b] *Università di Genova, Genova, Italy*

A. Benaglia [a], A. Beschi [b], L. Brianza [a,b], F. Brivio [a,b], V. Ciriolo [a,b,17], S. Di Guida [a,b,17], M.E. Dinardo [a,b], S. Fiorendi [a,b], S. Gennai [a], A. Ghezzi [a,b], P. Govoni [a,b], M. Malberti [a,b], S. Malvezzi [a], A. Massironi [a,b], D. Menasce [a], F. Monti, L. Moroni [a], M. Paganoni [a,b], D. Pedrini [a], S. Ragazzi [a,b], T. Tabarelli de Fatis [a,b], D. Zuolo [a,b]

[a] *INFN Sezione di Milano-Bicocca, Milano, Italy*
[b] *Università di Milano-Bicocca, Milano, Italy*

S. Buontempo [a], N. Cavallo [a,c], A. De Iorio [a,b], A. Di Crescenzo [a,b], F. Fabozzi [a,c], F. Fienga [a], G. Galati [a], A.O.M. Iorio [a,b], W.A. Khan [a], L. Lista [a], S. Meola [a,d,17], P. Paolucci [a,17], C. Sciacca [a,b], E. Voevodina [a,b]

[a] *INFN Sezione di Napoli, Napoli, Italy*
[b] *Università di Napoli 'Federico II', Napoli, Italy*
[c] *Università della Basilicata, Potenza, Italy*
[d] *Università G. Marconi, Roma, Italy*

P. Azzi [a], N. Bacchetta [a], D. Bisello [a,b], A. Boletti [a,b], A. Bragagnolo, R. Carlin [a,b], P. Checchia [a], M. Dall'Osso [a,b], P. De Castro Manzano [a], T. Dorigo [a], U. Dosselli [a], F. Gasparini [a,b], U. Gasparini [a,b], A. Gozzelino [a], S.Y. Hoh, S. Lacaprara [a], P. Lujan, M. Margoni [a,b], A.T. Meneguzzo [a,b], J. Pazzini [a,b], P. Ronchese [a,b], R. Rossin [a,b], F. Simonetto [a,b], A. Tiko, E. Torassa [a], M. Zanetti [a,b], P. Zotto [a,b], G. Zumerle [a,b]

[a] *INFN Sezione di Padova, Padova, Italy*
[b] *Università di Padova, Padova, Italy*
[c] *Università di Trento, Trento, Italy*

A. Braghieri [a], A. Magnani [a], P. Montagna [a,b], S.P. Ratti [a,b], V. Re [a], M. Ressegotti [a,b], C. Riccardi [a,b], P. Salvini [a], I. Vai [a,b], P. Vitulo [a,b]

[a] *INFN Sezione di Pavia, Pavia, Italy*
[b] *Università di Pavia, Pavia, Italy*

M. Biasini [a,b], G.M. Bilei [a], C. Cecchi [a,b], D. Ciangottini [a,b], L. Fanò [a,b], P. Lariccia [a,b], R. Leonardi [a,b], E. Manoni [a], G. Mantovani [a,b], V. Mariani [a,b], M. Menichelli [a], A. Rossi [a,b], A. Santocchia [a,b], D. Spiga [a]

[a] *INFN Sezione di Perugia, Perugia, Italy*
[b] *Università di Perugia, Perugia, Italy*

K. Androsov [a], P. Azzurri [a], G. Bagliesi [a], L. Bianchini [a], T. Boccali [a], L. Borrello, R. Castaldi [a], M.A. Ciocci [a,b], R. Dell'Orso [a], G. Fedi [a], F. Fiori [a,c], L. Giannini [a,c], A. Giassi [a], M.T. Grippo [a], F. Ligabue [a,c], E. Manca [a,c], G. Mandorli [a,c], A. Messineo [a,b], F. Palla [a], A. Rizzi [a,b], P. Spagnolo [a], R. Tenchini [a], G. Tonelli [a,b], A. Venturi [a], P.G. Verdini [a]

[a] *INFN Sezione di Pisa, Pisa, Italy*
[b] *Università di Pisa, Pisa, Italy*
[c] *Scuola Normale Superiore di Pisa, Pisa, Italy*

L. Barone [a,b], F. Cavallari [a], M. Cipriani [a,b], D. Del Re [a,b], E. Di Marco [a,b], M. Diemoz [a], S. Gelli [a,b], E. Longo [a,b], B. Marzocchi [a,b], P. Meridiani [a], G. Organtini [a,b], F. Pandolfi [a], R. Paramatti [a,b], F. Preiato [a,b], S. Rahatlou [a,b], C. Rovelli [a], F. Santanastasio [a,b]

[a] *INFN Sezione di Roma, Rome, Italy*
[b] *Sapienza Università di Roma, Rome, Italy*

N. Amapane [a,b], R. Arcidiacono [a,c], S. Argiro [a,b], M. Arneodo [a,c], N. Bartosik [a], R. Bellan [a,b], C. Biino [a], N. Cartiglia [a], F. Cenna [a,b], S. Cometti [a], M. Costa [a,b], R. Covarelli [a,b], N. Demaria [a], B. Kiani [a,b], C. Mariotti [a], S. Maselli [a], E. Migliore [a,b], V. Monaco [a,b], E. Monteil [a,b], M. Monteno [a], M.M. Obertino [a,b], L. Pacher [a,b],

N. Pastrone [a], M. Pelliccioni [a], G.L. Pinna Angioni [a,b], A. Romero [a,b], M. Ruspa [a,c], R. Sacchi [a,b], K. Shchelina [a,b], V. Sola [a], A. Solano [a,b], D. Soldi [a,b], A. Staiano [a]

[a] INFN Sezione di Torino, Torino, Italy
[b] Università di Torino, Torino, Italy
[c] Università del Piemonte Orientale, Novara, Italy

S. Belforte [a], V. Candelise [a,b], M. Casarsa [a], F. Cossutti [a], A. Da Rold [a,b], G. Della Ricca [a,b], F. Vazzoler [a,b], A. Zanetti [a]

[a] INFN Sezione di Trieste, Trieste, Italy
[b] Università di Trieste, Trieste, Italy

D.H. Kim, G.N. Kim, M.S. Kim, J. Lee, S. Lee, S.W. Lee, C.S. Moon, Y.D. Oh, S.I. Pak, S. Sekmen, D.C. Son, Y.C. Yang

Kyungpook National University, Daegu, Republic of Korea

H. Kim, D.H. Moon, G. Oh

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Republic of Korea

J. Goh [31], T.J. Kim

Hanyang University, Seoul, Republic of Korea

S. Cho, S. Choi, Y. Go, D. Gyun, S. Ha, B. Hong, Y. Jo, K. Lee, K.S. Lee, S. Lee, J. Lim, S.K. Park, Y. Roh

Korea University, Seoul, Republic of Korea

H.S. Kim

Sejong University, Seoul, Republic of Korea

J. Almond, J. Kim, J.S. Kim, H. Lee, K. Lee, K. Nam, S.B. Oh, B.C. Radburn-Smith, S.h. Seo, U.K. Yang, H.D. Yoo, G.B. Yu

Seoul National University, Seoul, Republic of Korea

D. Jeon, H. Kim, J.H. Kim, J.S.H. Lee, I.C. Park

University of Seoul, Seoul, Republic of Korea

Y. Choi, C. Hwang, J. Lee, I. Yu

Sungkyunkwan University, Suwon, Republic of Korea

V. Dudenas, A. Juodagalvis, J. Vaitkus

Vilnius University, Vilnius, Lithuania

I. Ahmed, Z.A. Ibrahim, M.A.B. Md Ali [32], F. Mohamad Idris [33], W.A.T. Wan Abdullah, M.N. Yusli, Z. Zolkapli

National Centre for Particle Physics, Universiti Malaya, Kuala Lumpur, Malaysia

J.F. Benitez, A. Castaneda Hernandez, J.A. Murillo Quijada

Universidad de Sonora (UNISON), Hermosillo, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, M.C. Duran-Osuna, I. Heredia-De La Cruz [34], R. Lopez-Fernandez, J. Mejia Guisao, R.I. Rabadan-Trejo, M. Ramirez-Garcia, G. Ramirez-Sanchez, R. Reyes-Almanza, A. Sanchez-Hernandez

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

S. Carrillo Moreno, C. Oropeza Barrera, F. Vazquez Valencia

Universidad Iberoamericana, Mexico City, Mexico

J. Eysermans, I. Pedraza, H.A. Salazar Ibarguen, C. Uribe Estrada

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

A. Morelos Pineda

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

D. Krofcheck

University of Auckland, Auckland, New Zealand

S. Bheesette, P.H. Butler

University of Canterbury, Christchurch, New Zealand

A. Ahmad, M. Ahmad, M.I. Asghar, Q. Hassan, H.R. Hoorani, A. Saddique, M.A. Shah, M. Shoaib, M. Waqas

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

H. Bialkowska, M. Bluj, B. Boimska, T. Frueboes, M. Górski, M. Kazana, M. Szleper, P. Traczyk, P. Zalewski

National Centre for Nuclear Research, Swierk, Poland

K. Bunkowski, A. Byszuk [35], K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski, M. Misiura, M. Olszewski, A. Pyskir, M. Walczak

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

M. Araujo, P. Bargassa, C. Beirão Da Cruz E Silva, A. Di Francesco, P. Faccioli, B. Galinhas, M. Gallinaro, J. Hollar, N. Leonardo, M.V. Nemallapudi, J. Seixas, G. Strong, O. Toldaiev, D. Vadruccio, J. Varela

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

S. Afanasiev, P. Bunin, M. Gavrilenko, I. Golutvin, I. Gorbunov, A. Kamenev, V. Karjavine, A. Lanev, A. Malakhov, V. Matveev [36,37], P. Moisenz, V. Palichik, V. Perelygin, S. Shmatov, S. Shulha, N. Skatchkov, V. Smirnov, N. Voytishin, A. Zarubin

Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim [38], E. Kuznetsova [39], P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, D. Sosnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, A. Karneyeu, M. Kirsanov, N. Krasnikov, A. Pashenkov, D. Tlisov, A. Toropin

Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, N. Lychkovskaya, V. Popov, I. Pozdnyakov, G. Safronov, A. Spiridonov, A. Stepennov, V. Stolin, M. Toms, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia

T. Aushev

Moscow Institute of Physics and Technology, Moscow, Russia

R. Chistov [40], M. Danilov [40], P. Parygin, D. Philippov, S. Polikarpov [40], E. Tarkovskii

National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin [37], M. Kirakosyan, S.V. Rusakov, A. Terkulov

P.N. Lebedev Physical Institute, Moscow, Russia

A. Baskakov, A. Belyaev, E. Boos, A. Demiyanov, A. Ershov, A. Gribushin, O. Kodolova, V. Korotkikh, I. Lokhtin, I. Miagkov, S. Obraztsov, S. Petrushanko, V. Savrin, A. Snigirev, I. Vardanyan

Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia

A. Barnyakov [41], V. Blinov [41], T. Dimova [41], L. Kardapoltsev [41], Y. Skovpen [41]

Novosibirsk State University (NSU), Novosibirsk, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, D. Elumakhov, A. Godizov, V. Kachanov, A. Kalinin, D. Konstantinov, P. Mandrik, V. Petrov, R. Ryutin, S. Slabospitskii, A. Sobol, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

Institute for High Energy Physics of National Research Centre 'Kurchatov Institute', Protvino, Russia

A. Babaev, S. Baidali, V. Okhotnikov

National Research Tomsk Polytechnic University, Tomsk, Russia

P. Adzic [42], P. Cirkovic, D. Devetak, M. Dordevic, J. Milosevic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

J. Alcaraz Maestre, A. Álvarez Fernández, I. Bachiller, M. Barrio Luna, J.A. Brochero Cifuentes, M. Cerrada, N. Colino, B. De La Cruz, A. Delgado Peris, C. Fernandez Bedoya, J.P. Fernández Ramos, J. Flix, M.C. Fouz, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, D. Moran, A. Pérez-Calero Yzquierdo, J. Puerta Pelayo, I. Redondo, L. Romero, M.S. Soares, A. Triossi

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain

J. Cuevas, C. Erice, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, J.R. González Fernández, E. Palencia Cortezon, V. Rodríguez Bouza, S. Sanchez Cruz, P. Vischia, J.M. Vizan Garcia

Universidad de Oviedo, Oviedo, Spain

I.J. Cabrillo, A. Calderon, B. Chazin Quero, J. Duarte Campderros, M. Fernandez, P.J. Fernández Manteca, A. García Alonso, J. Garcia-Ferrero, G. Gomez, A. Lopez Virto, J. Marco, C. Martinez Rivero, P. Martinez Ruiz del Arbol, F. Matorras, J. Piedra Gomez, C. Prieels, T. Rodrigo, A. Ruiz-Jimeno, L. Scodellaro, N. Trevisani, I. Vila, R. Vilar Cortabitarte

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

N. Wickramage

University of Ruhuna, Department of Physics, Matara, Sri Lanka

D. Abbaneo, B. Akgun, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, J. Bendavid, M. Bianco, A. Bocci, C. Botta, E. Brondolin, T. Camporesi, M. Cepeda, G. Cerminara, E. Chapon, Y. Chen, G. Cucciati, D. d'Enterria, A. Dabrowski, N. Daci, V. Daponte, A. David, A. De Roeck, N. Deelen, M. Dobson, M. Dünser, N. Dupont, A. Elliott-Peisert, P. Everaerts, F. Fallavollita [43], D. Fasanella, G. Franzoni, J. Fulcher, W. Funk, D. Gigi, A. Gilbert, K. Gill, F. Glege, M. Guilbaud, D. Gulhan, J. Hegeman, C. Heidegger, V. Innocente, A. Jafari, P. Janot, O. Karacheban [20], J. Kieseler, A. Kornmayer, M. Krammer [1], C. Lange, P. Lecoq, C. Lourenço, L. Malgeri, M. Mannelli, F. Meijers, J.A. Merlin, S. Mersi, E. Meschi, P. Milenovic [44], F. Moortgat, M. Mulders, J. Ngadiuba, S. Nourbakhsh, S. Orfanelli, L. Orsini, F. Pantaleo [17], L. Pape, E. Perez, M. Peruzzi, A. Petrilli, G. Petrucciani, A. Pfeiffer, M. Pierini, F.M. Pitters, D. Rabady, A. Racz,

T. Reis, G. Rolandi [45], M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, M. Seidel, M. Selvaggi, A. Sharma, P. Silva, P. Sphicas [46], A. Stakia, J. Steggemann, M. Tosi, D. Treille, A. Tsirou, V. Veckalns [47], M. Verzetti, W.D. Zeuner

CERN, European Organization for Nuclear Research, Geneva, Switzerland

L. Caminada [48], K. Deiters, W. Erdmann, R. Horisberger, Q. Ingram, H.C. Kaestli, D. Kotlinski, U. Langenegger, T. Rohe, S.A. Wiederkehr

Paul Scherrer Institut, Villigen, Switzerland

M. Backhaus, L. Bäni, P. Berger, N. Chernyavskaya, G. Dissertori, M. Dittmar, M. Donegà, C. Dorfer, T.A. Gómez Espinosa, C. Grab, D. Hits, T. Klijnsma, W. Lustermann, R.A. Manzoni, M. Marionneau, M.T. Meinhard, F. Micheli, P. Musella, F. Nessi-Tedaldi, J. Pata, F. Pauss, G. Perrin, L. Perrozzi, S. Pigazzini, M. Quittnat, C. Reissel, D. Ruini, D.A. Sanz Becerra, M. Schönenberger, L. Shchutska, V.R. Tavolaro, K. Theofilatos, M.L. Vesterbacka Olsson, R. Wallny, D.H. Zhu

ETH Zurich – Institute for Particle Physics and Astrophysics (IPA), Zurich, Switzerland

T.K. Aarrestad, C. Amsler [49], D. Brzhechko, M.F. Canelli, A. De Cosa, R. Del Burgo, S. Donato, C. Galloni, T. Hreus, B. Kilminster, S. Leontsinis, I. Neutelings, G. Rauco, P. Robmann, D. Salerno, K. Schweiger, C. Seitz, Y. Takahashi, A. Zucchetta

Universität Zürich, Zurich, Switzerland

Y.H. Chang, K.y. Cheng, T.H. Doan, R. Khurana, C.M. Kuo, W. Lin, A. Pozdnyakov, S.S. Yu

National Central University, Chung-Li, Taiwan

P. Chang, Y. Chao, K.F. Chen, P.H. Chen, W.-S. Hou, Arun Kumar, Y.F. Liu, R.-S. Lu, E. Paganis, A. Psallidas, A. Steen

National Taiwan University (NTU), Taipei, Taiwan

B. Asavapibhop, N. Srimanobhas, N. Suwonjandee

Chulalongkorn University, Faculty of Science, Department of Physics, Bangkok, Thailand

M.N. Bakirci [50], A. Bat, F. Boran, S. Cerci [51], S. Damarseckin, Z.S. Demiroglu, F. Dolek, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, Y. Guler, E. Gurpinar, I. Hos [52], C. Isik, E.E. Kangal [53], O. Kara, A. Kayis Topaksu, U. Kiminsu, M. Oglakci, G. Onengut, K. Ozdemir [54], A. Polatoz, U.G. Tok, S. Turkcapar, I.S. Zorbakir, C. Zorbilmez

Çukurova University, Physics Department, Science and Art Faculty, Adana, Turkey

B. Isildak [55], G. Karapinar [56], M. Yalvac, M. Zeyrek

Middle East Technical University, Physics Department, Ankara, Turkey

I.O. Atakisi, E. Gülmez, M. Kaya [57], O. Kaya [58], S. Ozkorucuklu [59], S. Tekten, E.A. Yetkin [60]

Bogazici University, Istanbul, Turkey

M.N. Agaras, A. Cakir, K. Cankocak, Y. Komurcu, S. Sen [61]

Istanbul Technical University, Istanbul, Turkey

B. Grynyov

Institute for Scintillation Materials of National Academy of Science of Ukraine, Kharkov, Ukraine

L. Levchuk

National Scientific Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

F. Ball, L. Beck, J.J. Brooke, D. Burns, E. Clement, D. Cussans, O. Davignon, H. Flacher, J. Goldstein, G.P. Heath, H.F. Heath, L. Kreczko, D.M. Newbold [62], S. Paramesvaran, B. Penning, T. Sakuma, D. Smith, V.J. Smith, J. Taylor, A. Titterton

University of Bristol, Bristol, United Kingdom

A. Belyaev [63], C. Brew, R.M. Brown, D. Cieri, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Linacre, E. Olaiya, D. Petyt, C.H. Shepherd-Themistocleous, A. Thea, I.R. Tomalin, T. Williams, W.J. Womersley

Rutherford Appleton Laboratory, Didcot, United Kingdom

R. Bainbridge, P. Bloch, J. Borg, S. Breeze, O. Buchmuller, A. Bundock, D. Colling, P. Dauncey, G. Davies, M. Della Negra, R. Di Maria, Y. Haddad, G. Hall, G. Iles, T. James, M. Komm, C. Laner, L. Lyons, A.-M. Magnan, S. Malik, A. Martelli, J. Nash [64], A. Nikitenko [7], V. Palladino, M. Pesaresi, D.M. Raymond, A. Richards, A. Rose, E. Scott, C. Seez, A. Shtipliyski, G. Singh, M. Stoye, T. Strebler, S. Summers, A. Tapper, K. Uchida, T. Virdee [17], N. Wardle, D. Winterbottom, J. Wright, S.C. Zenz

Imperial College, London, United Kingdom

J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, C.K. Mackay, A. Morton, I.D. Reid, L. Teodorescu, S. Zahid

Brunel University, Uxbridge, United Kingdom

K. Call, J. Dittmann, K. Hatakeyama, H. Liu, C. Madrid, B. Mcmaster, N. Pastika, C. Smith

Baylor University, Waco, USA

R. Bartek, A. Dominguez

Catholic University of America, Washington DC, USA

A. Buccilli, S.I. Cooper, C. Henderson, P. Rumerio, C. West

The University of Alabama, Tuscaloosa, USA

D. Arcaro, T. Bose, D. Gastler, D. Pinna, D. Rankin, C. Richardson, J. Rohlf, L. Sulak, D. Zou

Boston University, Boston, USA

G. Benelli, X. Coubez, D. Cutts, M. Hadley, J. Hakala, U. Heintz, J.M. Hogan [65], K.H.M. Kwok, E. Laird, G. Landsberg, J. Lee, Z. Mao, M. Narain, S. Sagir [66], R. Syarif, E. Usai, D. Yu

Brown University, Providence, USA

R. Band, C. Brainerd, R. Breedon, D. Burns, M. Calderon De La Barca Sanchez, M. Chertok, J. Conway, R. Conway, P.T. Cox, R. Erbacher, C. Flores, G. Funk, W. Ko, O. Kukral, R. Lander, M. Mulhearn, D. Pellett, J. Pilot, S. Shalhout, M. Shi, D. Stolp, D. Taylor, K. Tos, M. Tripathi, Z. Wang, F. Zhang

University of California, Davis, Davis, USA

M. Bachtis, C. Bravo, R. Cousins, A. Dasgupta, A. Florent, J. Hauser, M. Ignatenko, N. Mccoll, S. Regnard, D. Saltzberg, C. Schnaible, V. Valuev

University of California, Los Angeles, USA

E. Bouvier, K. Burt, R. Clare, J.W. Gary, S.M.A. Ghiasi Shirazi, G. Hanson, G. Karapostoli, E. Kennedy, F. Lacroix, O.R. Long, M. Olmedo Negrete, M.I. Paneva, W. Si, L. Wang, H. Wei, S. Wimpenny, B.R. Yates

University of California, Riverside, Riverside, USA

J.G. Branson, P. Chang, S. Cittolin, M. Derdzinski, R. Gerosa, D. Gilbert, B. Hashemi, A. Holzner, D. Klein, G. Kole, V. Krutelyov, J. Letts, M. Masciovecchio, D. Olivito, S. Padhi, M. Pieri, M. Sani, V. Sharma, S. Simon, M. Tadel, A. Vartak, S. Wasserbaech [67], J. Wood, F. Würthwein, A. Yagil, G. Zevi Della Porta

University of California, San Diego, La Jolla, USA

N. Amin, R. Bhandari, J. Bradmiller-Feld, C. Campagnari, M. Citron, A. Dishaw, V. Dutta, M. Franco Sevilla, L. Gouskos, R. Heller, J. Incandela, A. Ovcharova, H. Qu, J. Richman, D. Stuart, I. Suarez, S. Wang, J. Yoo

University of California, Santa Barbara – Department of Physics, Santa Barbara, USA

D. Anderson, A. Bornheim, J.M. Lawhorn, H.B. Newman, T.Q. Nguyen, M. Spiropulu, J.R. Vlimant, R. Wilkinson, S. Xie, Z. Zhang, R.Y. Zhu

California Institute of Technology, Pasadena, USA

M.B. Andrews, T. Ferguson, T. Mudholkar, M. Paulini, M. Sun, I. Vorobiev, M. Weinberg

Carnegie Mellon University, Pittsburgh, USA

J.P. Cumalat, W.T. Ford, F. Jensen, A. Johnson, M. Krohn, E. MacDonald, T. Mulholland, R. Patel, A. Perloff, K. Stenson, K.A. Ulmer, S.R. Wagner

University of Colorado Boulder, Boulder, USA

J. Alexander, J. Chaves, Y. Cheng, J. Chu, A. Datta, K. Mcdermott, N. Mirman, J.R. Patterson, D. Quach, A. Rinkevicius, A. Ryd, L. Skinnari, L. Soffi, S.M. Tan, Z. Tao, J. Thom, J. Tucker, P. Wittich, M. Zientek

Cornell University, Ithaca, USA

S. Abdullin, M. Albrow, M. Alyari, G. Apollinari, A. Apresyan, A. Apyan, S. Banerjee, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, K. Burkett, J.N. Butler, A. Canepa, G.B. Cerati, H.W.K. Cheung, F. Chlebana, M. Cremonesi, J. Duarte, V.D. Elvira, J. Freeman, Z. Gecse, E. Gottschalk, L. Gray, D. Green, S. Grünendahl, O. Gutsche, J. Hanlon, R.M. Harris, S. Hasegawa, J. Hirschauer, Z. Hu, B. Jayatilaka, S. Jindariani, M. Johnson, U. Joshi, B. Klima, M.J. Kortelainen, B. Kreis, S. Lammel, D. Lincoln, R. Lipton, M. Liu, T. Liu, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, P. Merkel, S. Mrenna, S. Nahn, V. O'Dell, K. Pedro, C. Pena, O. Prokofyev, G. Rakness, L. Ristori, A. Savoy-Navarro [68], B. Schneider, E. Sexton-Kennedy, A. Soha, W.J. Spalding, L. Spiegel, S. Stoynev, J. Strait, N. Strobbe, L. Taylor, S. Tkaczyk, N.V. Tran, L. Uplegger, E.W. Vaandering, C. Vernieri, M. Verzocchi, R. Vidal, M. Wang, H.A. Weber, A. Whitbeck

Fermi National Accelerator Laboratory, Batavia, USA

D. Acosta, P. Avery, P. Bortignon, D. Bourilkov, A. Brinkerhoff, L. Cadamuro, A. Carnes, M. Carver, D. Curry, R.D. Field, S.V. Gleyzer, B.M. Joshi, J. Konigsberg, A. Korytov, K.H. Lo, P. Ma, K. Matchev, H. Mei, G. Mitselmakher, D. Rosenzweig, K. Shi, D. Sperka, J. Wang, S. Wang, X. Zuo

University of Florida, Gainesville, USA

Y.R. Joshi, S. Linn

Florida International University, Miami, USA

A. Ackert, T. Adams, A. Askew, S. Hagopian, V. Hagopian, K.F. Johnson, T. Kolberg, G. Martinez, T. Perry, H. Prosper, A. Saha, C. Schiber, R. Yohay

Florida State University, Tallahassee, USA

M.M. Baarmand, V. Bhopatkar, S. Colafranceschi, M. Hohlmann, D. Noonan, M. Rahmani, T. Roy, F. Yumiceva

Florida Institute of Technology, Melbourne, USA

M.R. Adams, L. Apanasevich, D. Berry, R.R. Betts, R. Cavanaugh, X. Chen, S. Dittmer, O. Evdokimov, C.E. Gerber, D.A. Hangal, D.J. Hofman, K. Jung, J. Kamin, C. Mills, I.D. Sandoval Gonzalez, M.B. Tonjes, H. Trauger, N. Varelas, H. Wang, X. Wang, Z. Wu, J. Zhang

University of Illinois at Chicago (UIC), Chicago, USA

M. Alhusseini, B. Bilki [69], W. Clarida, K. Dilsiz [70], S. Durgut, R.P. Gandrajula, M. Haytmyradov, V. Khristenko, J.-P. Merlo, A. Mestvirishvili, A. Moeller, J. Nachtman, H. Ogul [71], Y. Onel, F. Ozok [72], A. Penzo, C. Snyder, E. Tiras, J. Wetzel

The University of Iowa, Iowa City, USA

B. Blumenfeld, A. Cocoros, N. Eminizer, D. Fehling, L. Feng, A.V. Gritsan, W.T. Hung, P. Maksimovic, J. Roskes, U. Sarica, M. Swartz, M. Xiao, C. You

Johns Hopkins University, Baltimore, USA

A. Al-bataineh, P. Baringer, A. Bean, S. Boren, J. Bowen, A. Bylinkin, J. Castle, S. Khalil, A. Kropivnitskaya, D. Majumder, W. Mcbrayer, M. Murray, C. Rogan, S. Sanders, E. Schmitz, J.D. Tapia Takaki, Q. Wang

The University of Kansas, Lawrence, USA

S. Duric, A. Ivanov, K. Kaadze, D. Kim, Y. Maravin, D.R. Mendis, T. Mitchell, A. Modak, A. Mohammadi, L.K. Saini, N. Skhirtladze

Kansas State University, Manhattan, USA

F. Rebassoo, D. Wright

Lawrence Livermore National Laboratory, Livermore, USA

A. Baden, O. Baron, A. Belloni, S.C. Eno, Y. Feng, C. Ferraioli, N.J. Hadley, S. Jabeen, G.Y. Jeng, R.G. Kellogg, J. Kunkle, A.C. Mignerey, S. Nabili, F. Ricci-Tam, Y.H. Shin, A. Skuja, S.C. Tonwar, K. Wong

University of Maryland, College Park, USA

D. Abercrombie, B. Allen, V. Azzolini, A. Baty, G. Bauer, R. Bi, S. Brandt, W. Busza, I.A. Cali, M. D'Alfonso, Z. Demiragli, G. Gomez Ceballos, M. Goncharov, P. Harris, D. Hsu, M. Hu, Y. Iiyama, G.M. Innocenti, M. Klute, D. Kovalskyi, Y.-J. Lee, P.D. Luckey, B. Maier, A.C. Marini, C. Mcginn, C. Mironov, S. Narayanan, X. Niu, C. Paus, C. Roland, G. Roland, G.S.F. Stephans, K. Sumorok, K. Tatar, D. Velicanu, J. Wang, T.W. Wang, B. Wyslouch, S. Zhaozhong

Massachusetts Institute of Technology, Cambridge, USA

A.C. Benvenuti [†], R.M. Chatterjee, A. Evans, P. Hansen, Sh. Jain, S. Kalafut, Y. Kubota, Z. Lesko, J. Mans, N. Ruckstuhl, R. Rusack, J. Turkewitz, M.A. Wadud

University of Minnesota, Minneapolis, USA

J.G. Acosta, S. Oliveros

University of Mississippi, Oxford, USA

E. Avdeeva, K. Bloom, D.R. Claes, C. Fangmeier, F. Golf, R. Gonzalez Suarez, R. Kamalieddin, I. Kravchenko, J. Monroy, J.E. Siado, G.R. Snow, B. Stieger

University of Nebraska-Lincoln, Lincoln, USA

A. Godshalk, C. Harrington, I. Iashvili, A. Kharchilava, C. Mclean, D. Nguyen, A. Parker, S. Rappoccio, B. Roozbahani

State University of New York at Buffalo, Buffalo, USA

G. Alverson, E. Barberis, C. Freer, A. Hortiangtham, D.M. Morse, T. Orimoto, R. Teixeira De Lima, T. Wamorkar, B. Wang, A. Wisecarver, D. Wood

Northeastern University, Boston, USA

S. Bhattacharya, O. Charaf, K.A. Hahn, N. Mucia, N. Odell, M.H. Schmitt, K. Sung, M. Trovato, M. Velasco

Northwestern University, Evanston, USA

R. Bucci, N. Dev, M. Hildreth, K. Hurtado Anampa, C. Jessop, D.J. Karmgard, N. Kellams, K. Lannon, W. Li, N. Loukas, N. Marinelli, F. Meng, C. Mueller, Y. Musienko [36], M. Planer, A. Reinsvold, R. Ruchti, P. Siddireddy, G. Smith, S. Taroni, M. Wayne, A. Wightman, M. Wolf, A. Woodard

University of Notre Dame, Notre Dame, USA

J. Alimena, L. Antonelli, B. Bylsma, L.S. Durkin, S. Flowers, B. Francis, A. Hart, C. Hill, W. Ji, T.Y. Ling, W. Luo, B.L. Winer

The Ohio State University, Columbus, USA

S. Cooperstein, P. Elmer, J. Hardenbrook, S. Higginbotham, A. Kalogeropoulos, D. Lange, M.T. Lucchini, J. Luo, D. Marlow, K. Mei, I. Ojalvo, J. Olsen, C. Palmer, P. Piroué, J. Salfeld-Nebgen, D. Stickland, C. Tully

Princeton University, Princeton, USA

S. Malik, S. Norberg

University of Puerto Rico, Mayaguez, USA

A. Barker, V.E. Barnes, S. Das, L. Gutay, M. Jones, A.W. Jung, A. Khatiwada, B. Mahakud, D.H. Miller, N. Neumeister, C.C. Peng, S. Piperov, H. Qiu, J.F. Schulte, J. Sun, F. Wang, R. Xiao, W. Xie

Purdue University, West Lafayette, USA

T. Cheng, J. Dolen, N. Parashar

Purdue University Northwest, Hammond, USA

Z. Chen, K.M. Ecklund, S. Freed, F.J.M. Geurts, M. Kilpatrick, W. Li, B.P. Padley, R. Redjimi, J. Roberts, J. Rorie, W. Shi, Z. Tu, J. Zabel, A. Zhang

Rice University, Houston, USA

A. Bodek, P. de Barbaro, R. Demina, Y.t. Duh, J.L. Dulemba, C. Fallon, T. Ferbel, M. Galanti, A. Garcia-Bellido, J. Han, O. Hindrichs, A. Khukhunaishvili, P. Tan, R. Taus

University of Rochester, Rochester, USA

A. Agapitos, J.P. Chou, Y. Gershtein, E. Halkiadakis, M. Heindl, E. Hughes, S. Kaplan, R. Kunnawalkam Elayavalli, S. Kyriacou, A. Lath, R. Montalvo, K. Nash, M. Osherson, H. Saka, S. Salur, S. Schnetzer, D. Sheffield, S. Somalwar, R. Stone, S. Thomas, P. Thomassen, M. Walker

Rutgers, The State University of New Jersey, Piscataway, USA

A.G. Delannoy, J. Heideman, G. Riley, S. Spanier

University of Tennessee, Knoxville, USA

O. Bouhali [73], A. Celik, M. Dalchenko, M. De Mattia, A. Delgado, S. Dildick, R. Eusebi, J. Gilmore, T. Huang, T. Kamon [74], S. Luo, R. Mueller, D. Overton, L. Pernié, D. Rathjens, A. Safonov

Texas A&M University, College Station, USA

N. Akchurin, J. Damgov, F. De Guio, P.R. Dudero, S. Kunori, K. Lamichhane, S.W. Lee, T. Mengke, S. Muthumuni, T. Peltola, S. Undleeb, I. Volobouev, Z. Wang

Texas Tech University, Lubbock, USA

S. Greene, A. Gurrola, R. Janjam, W. Johns, C. Maguire, A. Melo, H. Ni, K. Padeken, J.D. Ruiz Alvarez, P. Sheldon, S. Tuo, J. Velkovska, M. Verweij, Q. Xu

Vanderbilt University, Nashville, USA

M.W. Arenton, P. Barria, B. Cox, R. Hirosky, M. Joyce, A. Ledovskoy, H. Li, C. Neu, T. Sinthuprasith, Y. Wang, E. Wolfe, F. Xia

University of Virginia, Charlottesville, USA

R. Harr, P.E. Karchin, N. Poudyal, J. Sturdy, P. Thapa, S. Zaleski

Wayne State University, Detroit, USA

M. Brodski, J. Buchanan, C. Caillol, D. Carlsmith, S. Dasu, L. Dodd, B. Gomber, M. Grothe, M. Herndon, A. Hervé, U. Hussain, P. Klabbers, A. Lanaro, K. Long, R. Loveless, T. Ruggles, A. Savin, V. Sharma, N. Smith, W.H. Smith, N. Woods

University of Wisconsin – Madison, Madison, WI, USA

[†] Deceased.
[1] Also at Vienna University of Technology, Vienna, Austria.
[2] Also at IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France.
[3] Also at Universidade Estadual de Campinas, Campinas, Brazil.
[4] Also at Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
[5] Also at Université Libre de Bruxelles, Bruxelles, Belgium.
[6] Also at University of Chinese Academy of Sciences, Beijing, China.
[7] Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
[8] Also at Joint Institute for Nuclear Research, Dubna, Russia.
[9] Now at Cairo University, Cairo, Egypt.
[10] Also at Fayoum University, El-Fayoum, Egypt.
[11] Now at British University in Egypt, Cairo, Egypt.
[12] Also at Department of Physics, King Abdulaziz University, Jeddah, Saudi Arabia.
[13] Also at Université de Haute Alsace, Mulhouse, France.
[14] Also at Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia.
[15] Also at Tbilisi State University, Tbilisi, Georgia.
[16] Also at Ilia State University, Tbilisi, Georgia.
[17] Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
[18] Also at RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany.
[19] Also at University of Hamburg, Hamburg, Germany.
[20] Also at Brandenburg University of Technology, Cottbus, Germany.
[21] Also at MTA-ELTE Lendület CMS Particle and Nuclear Physics Group, Eötvös Loránd University, Budapest, Hungary.
[22] Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
[23] Also at Institute of Physics, University of Debrecen, Debrecen, Hungary.
[24] Also at Indian Institute of Technology Bhubaneswar, Bhubaneswar, India.
[25] Also at Institute of Physics, Bhubaneswar, India.
[26] Also at Shoolini University, Solan, India.
[27] Also at University of Visva-Bharati, Santiniketan, India.
[28] Also at Isfahan University of Technology, Isfahan, Iran.
[29] Also at Plasma Physics Research Center, Science and Research Branch, Islamic Azad University, Tehran, Iran.
[30] Also at Università degli Studi di Siena, Siena, Italy.
[31] Also at Kyunghee University, Seoul, Republic of Korea.
[32] Also at International Islamic University of Malaysia, Kuala Lumpur, Malaysia.
[33] Also at Malaysian Nuclear Agency, MOSTI, Kajang, Malaysia.
[34] Also at Consejo Nacional de Ciencia y Tecnología, Mexico city, Mexico.
[35] Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland.
[36] Also at Institute for Nuclear Research, Moscow, Russia.
[37] Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia.
[38] Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia.
[39] Also at University of Florida, Gainesville, USA.
[40] Also at P.N. Lebedev Physical Institute, Moscow, Russia.
[41] Also at Budker Institute of Nuclear Physics, Novosibirsk, Russia.
[42] Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia.
[43] Also at INFN Sezione di Pavia [a], Università di Pavia [b], Pavia, Italy.
[44] Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
[45] Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy.
[46] Also at National and Kapodistrian University of Athens, Athens, Greece.
[47] Also at Riga Technical University, Riga, Latvia.
[48] Also at Universität Zürich, Zurich, Switzerland.
[49] Also at Stefan Meyer Institute for Subatomic Physics (SMI), Vienna, Austria.
[50] Also at Gaziosmanpasa University, Tokat, Turkey.
[51] Also at Adiyaman University, Adiyaman, Turkey.
[52] Also at Istanbul Aydin University, Istanbul, Turkey.

[53] Also at Mersin University, Mersin, Turkey.
[54] Also at Piri Reis University, Istanbul, Turkey.
[55] Also at Ozyegin University, Istanbul, Turkey.
[56] Also at Izmir Institute of Technology, Izmir, Turkey.
[57] Also at Marmara University, Istanbul, Turkey.
[58] Also at Kafkas University, Kars, Turkey.
[59] Also at Istanbul University, Faculty of Science, Istanbul, Turkey.
[60] Also at Istanbul Bilgi University, Istanbul, Turkey.
[61] Also at Hacettepe University, Ankara, Turkey.
[62] Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
[63] Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
[64] Also at Monash University, Faculty of Science, Clayton, Australia.
[65] Also at Bethel University, St. Paul, USA.
[66] Also at Karamanoğlu Mehmetbey University, Karaman, Turkey.
[67] Also at Utah Valley University, Orem, USA.
[68] Also at Purdue University, West Lafayette, USA.
[69] Also at Beykent University, Istanbul, Turkey.
[70] Also at Bingol University, Bingol, Turkey.
[71] Also at Sinop University, Sinop, Turkey.
[72] Also at Mimar Sinan University, Istanbul, Istanbul, Turkey.
[73] Also at Texas A&M University at Qatar, Doha, Qatar.
[74] Also at Kyungpook National University, Daegu, Republic of Korea.